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Productivity of Western Forests: A Forest Products Focus

TECHNICAL EDITORS

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ABSTRACT

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In August 20-23, 2004, a conference was held in Kamilche, WA, with the title "Productivity of Western Forests: A Forest Products Focus." The meeting brought together researchers and practitioners interested in discussing the economic and biological factors influencing wood production and value. One of the underlying assumptions of the meeting organizers was that management activities would be practiced within a framework of sustaining or improving site productivity; thus, several papers deal with methods to protect or improve productivity or discuss new studies designed to test the effects of various practices. This proceedings includes 11 papers based on oral presentations at the conference, 3 papers based on posters and 2 papers describing the Fall River and Matlock Long-Term Site Productivity study areas visited on the field tours. The papers cover subjects on forest harvesting activities, stand establishment, silviculture, site productivity, remote sensing, and wood product technologies.

KEYWORDS: Site productivity, forest harvesting, stand establishment, silviculture, forest products, Western forests, LIDAR, log quality, tree quality.

PREFACE

During September 20-23, 2004, we held a conference, "Productivity of Western Forests: A Forest Products Focus," at the Little Creek Hotel and Casino in Kamilche, Washington. The conference was sponsored by Oregon State University College of Forestry, Pacific Northwest Research Station, Western Forestry and Conservation Association, and Northwest Forest Soils Council. The primary goal of the conference was to bring together people interested in managing Western forests for the production of forest products. Many conferences held in recent years have focused on managing forests for wildlife habitat, biodiversity, or other nontimber objectives, but there has been relatively limited current information available on (1) markets for wood products, (2) contemporary harvesting operations, (3) silvicultural practices (especially for stand establishment), and (4) emerging technologies for remote measurement of trees and determination of stand and log characteristics that influence marketability.

The main members of the steering committee were: Stephen Schoenholtz, committee chair, Oregon State University; Bernard Bormann, Pacific Northwest Research Station; David Briggs, University of Washington; Scott Chang, University of Alberta; Mike Curran, British Columbia Ministry of Forests; Randall Greggs, Green Diamond Resource Company; Connie Harrington, Pacific Northwest Research Station; Tim Harrington, Pacific Northwest Research Station; Rob Harrison, University of Washington; Ron Heninger, Weyerhaeuser Company; Bob Powers, Pacific Southwest Research Station; Tom Terry, Weyerhaeuser Company; Eric Turnblom, University of Washington; Joanna Warren, Oregon State University; and Richard Zabel, Western Forestry and Conservation Association. Additional input was provided by Debbie Page-Dumroese, Rocky Mountain Research Station.

Conference organizers wanted to highlight potential effects of forest practices on short- and long-term productivity. This was accomplished through a preconference tour of the Fall River Long-Term Site Productivity Study (west of Chehalis, Washington) and a midconference tour of the Matlock Long-Term Site Productivity Study (west of Shelton, Washington). The midconference tour also visited the Simpson Timber Company small-log mill at Dayton, Washington, and attendees had the opportunity to participate in demonstrations of new equipment for testing wood quality in standing trees and logs.

The conference included 17 invited talks, 10 poster presentations, and 2 tours. Speakers were invited to submit a paper; poster presenters and field-trip organizers were invited to submit an abstract or mini-paper. Eleven speakers, three poster presenters, and two field-trip presenters responded to our invitation to contribute to this proceedings. The papers that follow are organized by topic area in the order that they were presented at the conference, followed by the posters in alphabetical order, and then by summaries of the two field-trip stops at the Fall River and Matlock study sites.

We thank Grace Douglass and Joseph Kraft for assistance in preparing the manuscripts for publication.

This is a product of the Sustainable Forestry Component of Agenda 2020, a joint effort of the USDA Forest Service Research & Development and the American Forest and Paper Association. Funds were provided by the Forest Service Research & Development, Washington Office.

We hope you find the information to be timely and of interest.

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Pacific Northwest Research Station

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HARVESTING EFFECTS ON SOILS, TREE GROWTH, AND LONG-TERM PRODUCTIVITY

Michael P. Curran[1], Ronald L. Heninger[2], Douglas G. Maynard[3], and Robert F. Powers[4]

ABSTRACT

Soil disturbance related to timber harvesting, reforestation, or stand tending is mainly a result of moving equipment and trees. Compaction and organic matter removal are of primary concern. Severity and extent of disturbance depend on harvest system, soil and climatic conditions. On-site, long-term effects range from permanent loss of growing sites to roads, to more subtle changes in soil properties that ultimately influence site productivity. Off-site effects may include erosion and landslides. Soil disturbance during operations is regulated and monitored to minimize both on- and off-site effects, which can take years or decades to appear. At national and international levels, sustainability protocols recognize forest soil disturbance as an important issue. At the regional level, continual monitoring and testing of standards, practices, and effects, is necessary for the successful implementation of sustainable soil management. In western forests, few studies are old enough to conclusively predict the long-term effects of harvest-induced soil disturbance on tree growth. Results from existing long- and short-term studies have demonstrated a full range of possible productivity outcomes. The net effect depends on which growth-limiting factors have been influenced by disturbance. Refinement of policies will occur as existing studies like the Long-term Soil Productivity (LTSP) network reach critical, predictive stand ages. In the interim, some regional trends are apparent: deeply developed, moderately coarse textured soils appear less sensitive to disturbance. Conversely, shallower and/or finer textured soils appear more sensitive.

KEYWORDS: Criteria and indicators, organic matter depletion, soil disturbance, soil compaction, sustainability protocols.

INTRODUCTION

For forest productivity, sustainable development can be defined as ensuring the biological, chemical and physical integrity of the soil remains for future generations. Sustainability must be addressed throughout all facets of forest management including implementation of individual harvest or stand-tending plans, development of agency or company standards and best management practices (BMPs), and third-party certification. Sustainable development is promoted through reporting procedures required by applicable sustainability protocols, and by having third-party certification of forest practices and products.

Sustainability protocols exist at international and national levels. At the international level, the Montreal Process (MP) includes a Working Group on Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forests (Montreal Process Working Group 1997). Some countries have developed their own protocols and procedures designed to track and report progress toward meeting requirements of international protocols such as the MP. For example, the Canadian Council of Forest Ministers recently developed revised criteria and indicators for sustainable forest management (CCFM 2003).

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Third-party (eco) certification of forest practices and resulting wood products has arisen in response to sustainability protocols and the greening of the global market place. Organizations such as Sustainable Forestry Initiative (American Forest and Paper Association), Canadian Standards Association, Forest Stewardship Council (FSC), and ISO 1400.1 all have documented review processes and procedures for certification. Protecting streams and natural drainage patterns, maintaining slope stability, and regulating soil disturbance are common elements considered. In addition, most require some adaptive management process to ensure continuous improvement of practices on the ground. Compliance with current soil disturbance standards is often used as a proxy for ensuring sustainability. Some call for more restrictive standards than others (e.g., FSC in British Columbia calls for lower disturbance levels than Provincial regulations).

When managing harvest effects on soils, tree growth and long-term productivity at the local level, managers usually focus on reducing soil disturbance from mechanical operations. Soil disturbance occurring at time of harvest can have negative, positive, or no detectable effect on growth or hydrologic function. Soil disturbance at the time of operations is often an indicator used in regulating long-term productivity and hydrologic effects. This is because in many North American ecosystems, we need at least 10 to 20 years of data to draw conclusions about the effects of various practices. In discussing evidence for long-term productivity changes, Morris and Miller (1994) indicated slow-growing stands require 20 or more years of growth before long-term productivity consequences can be ascertained. Soil disturbance is the proxy that we can observe and regulate at the time of harvesting, site preparation, etc. A common approach is needed for describing soil disturbance so that results achieved in different areas are comparable (Curran et al. in prep.).

In this paper, we discuss effects of harvest induced soil disturbance on subsequent tree growth. Long-term productivity implications are explored along with some soil considerations in harvest planning and continuous improvement schemes. More detailed discussion of these effects and practical interpretations are provided in the literature that has been cited, guidebook materials available from government agencies like the B.C. Ministry of Forests (http://www.gov.bc.ca/for), the USDA Forest Service (http://www.fs.fed.us/), various University extension websites, and related products like the new Forestry Handbook for B.C. (soils chapter by Krzic and Curran, in press).

HARVESTING EFFECTS ON SOILS

Soil disturbance can be defined as any physical, biological, or chemical alteration of the soil caused by forestry operations. The examples of soil disturbance we provide here are primarily related to harvesting activities. Effects on tree growth may be inconsequential, beneficial or detrimental, depending on the net effect on growth-limiting factors and hydrologic properties. Soil disturbance can be considered in the context of: (1) the necessary permanent access network and (2) disturbance that occurs within individual harvest areas that will be reforested and managed as forest land.

Permanent Access Network (Roads, Trails, Landings)

The permanent access network is part of the infrastructure required to transport timber and manage forest land. Standards are in place for transportation system development because it represents a permanent removal of growing sites from the land base, and can have long-term effects both on- and off-site. Effects can include drainage interception and disruption, as well as erosion and sediment delivery to streams, which can affect other resource values, and can also cause property damage and possibly loss of life in catastrophic events. These are all good reasons to minimize the amount of forest land lost to permanent access.

In-Block Disturbance (Area to be Reforested)

Most in-block soil disturbance is the result of harvest equipment and dragging logs. Effects of soil disturbance depend on harvest method and season of operation. Ground-based harvesting typically creates more disturbance than aerial or cable. Wet season harvest is typically more disturbing than dry season harvest, or winter condition harvest (where that option exists). Severity and extent of in-block disturbance can be controlled or minimized through careful harvest planning and practices. Guidelines, regulations and standards often limit types and extent of disturbance and commonly focus on compaction and displacement.

Fully mechanized harvest activities, where feller-buncher and grapple skidder operations are allowed off main skidtrails, can result in high amounts of soil disturbance. Examples of the type and amounts of soil disturbance that can occur from this type of harvest are shown in figure 1. Total machine traffic coverage on the soil ranged from 49% to 62 %. The amount of concentrated disturbance complied with the guidelines at the time of harvest. Repair of concentrated disturbance is often possible with rehabilitation techniques; however, extensive off-trail disturbance is more problematic if it has damaged the soil. The main concern with off-trail traffic is compaction.

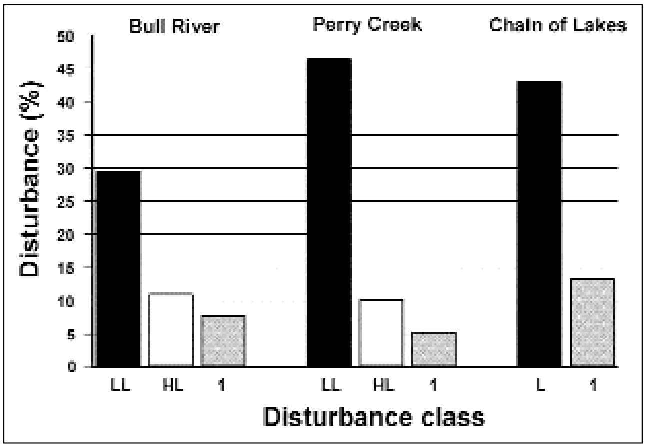

Figure 1—An example of soil disturbance coverage from mechanized harvesting in the Southern Rocky Mountain Trench British Columbia, 1991 (Curran 1999). (LL = light traffic trails; HL = heavy traffic trails – main skid roads; 1 = 5 & 10 cm deep ruts; L at Chain of Lakes includes both LL and HL.)

Figure 2—Close-up of an example of significant compaction from a heavy traffic trail at the Perry Creek site (see Fig. 1). Note the coarse platy structure that often results from heavy compaction of these study soils.

Compaction and Puddling

Compaction and puddling result in alteration and/or loss of soil structure with the affected soil often appearing coarse platy or massive (figure 2). Guidelines define thresholds for compaction severity and spatial extent, beyond which it is generally thought to have a long-term effect on forest productivity or hydrologic function. Compaction results from the weight and vibration of heavy equipment and dragging of logs. Important effects of compaction on forest soils are:

1. Soil density and strength are often increased,
2. Soil macro-porosity is often decreased, and
3. Soil infiltration is often decreased.

Bulk density increases are often measured in terms of total soil or fine fraction bulk density. Neither of these may be a true measure of other effects (e.g., soil porosity and penetration resistance) because trafficking sometimes incorporates considerable amounts of organic matter in the soil. Incorporation of forest floor and other organic material into a soil can result in increased puddling of soils due to clay-sized particles settling under wet conditions, or being smeared by equipment traffic.

Penetration resistance can be a good measure of relative compaction and conditions of high soil strength can restrict root growth. However, penetrometer readings are dependent on soil moisture content at the time and observations are affected by soil texture, and the amount of coarse fragments and roots. Figure 3 shows how compaction increases soil strength as measured by penetration resistance. Soil moisture content often varies between disturbance types due to differences in hydrologic properties (discussed below). However, while strength is affected by soil moisture and clay content, soils in areas severly disturbed invariably test higher than undisturbed soil, regardless of soil moisture. Figure 3 also demonstrates that most compaction occurs in the top 20 cm. Compaction increases with increasing traffic, and most compaction occurs during the first trips over the same piece of ground; as few as three passes can result in most of the compaction.

Perhaps the most important compaction effect is alteration of soil porosity, due to the collapse or distortion of large macro-pores. Soil compaction increased bulk density on a loam soil resulting in an overall decrease in aeration porosity and slight increases in available and unavailable water (figure 4). Less biological activity occurs as aeration porosity decreases. Once aeration porosity drops below 10% (at 0.01 MPa tension in a standard laboratory test) gas diffusion in the soil is essentially zero (Xu et al. 1992). This is thought to be a result of the tortuous nature of remaining large soil pores and restrictions in the necks between pores.

Another potential result of soil compaction is altered hydrologic function. Saturated hydraulic conductivity can decrease substantially in compacted soils (fig. 5). Infiltration decreases in compacted soil can result in increased surface runoff and consequently less water storage. Soil compaction may or may not impact plant growth detrimentally. Gomez et al. (2002), Powers (1999) and Powers et al. (in review) found that for sandy soils and drier sites, compaction actually improved growth by improving water availability. Interestingly, soil microbial activity may be unaffected by soil compaction. Unless soils are poorly drained, microbial activity probably continues unabated in

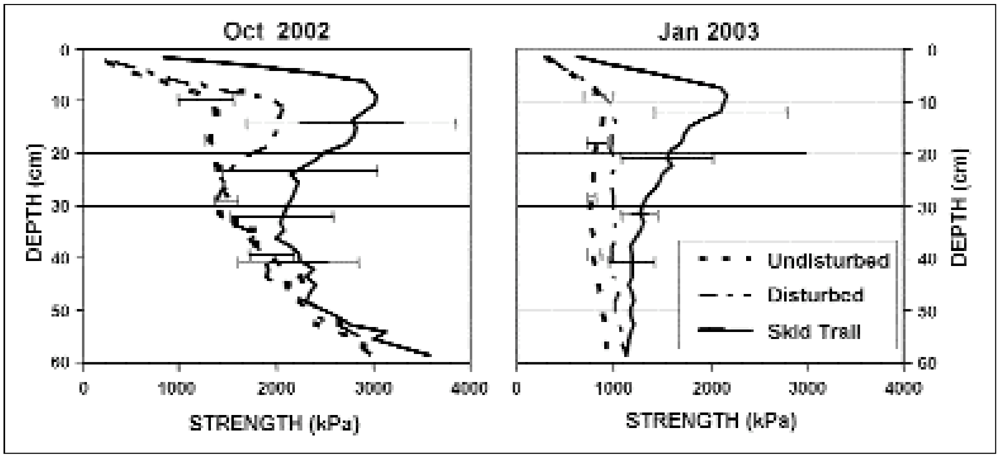

Figure 3—Iron Canyon soil monitoring to determine disturbance severity following second harvest. Penetrometer profiles by disturbance class, October 2002 (21% soil moisture), and January 2003 (45 % soil moisture) (Unpublished data on file at the USFS, PSW Research Station, Redding, California.)

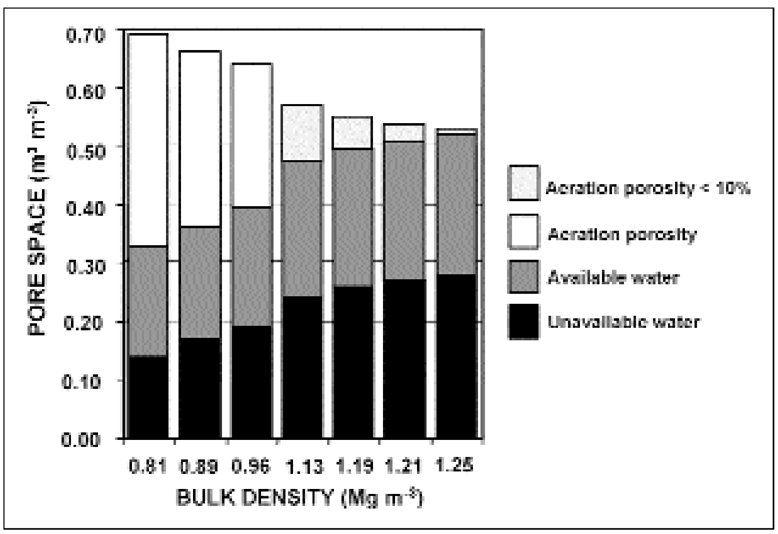

Figure 4—Effect of soil compaction on pore size distribution and water availability, Cohasset Loam studied by Siegel-Issem et al. (2005).

small soil pores and micro-aggregates that are not reduced by compaction (Shestak and Busse 2005).

Severity and extent of compaction are determined by both controlling and manageable factors (modified from Lewis et al. 1989).

Controlling factors are those inherent to the harvest site and include:

- texture,
- coarse fragments,
- forest floor depth/type,
- soil depth, and
- mineralogy.

Manageable factors can be controlled through harvest planning and include:

- machine traffic,
- machine type/dynamic loading,
- seasonal soil conditions (wetness, snow, frozen soil), and
- machine operator awareness, training, and skill.

Various hazard, or risk (hazard times consequence) rating schemes have been developed to evaluate the susceptibility of soils to compaction. One example that focuses on controlling site factors is the B.C. Ministry of Forests compaction hazard key (Curran et al. 2000).

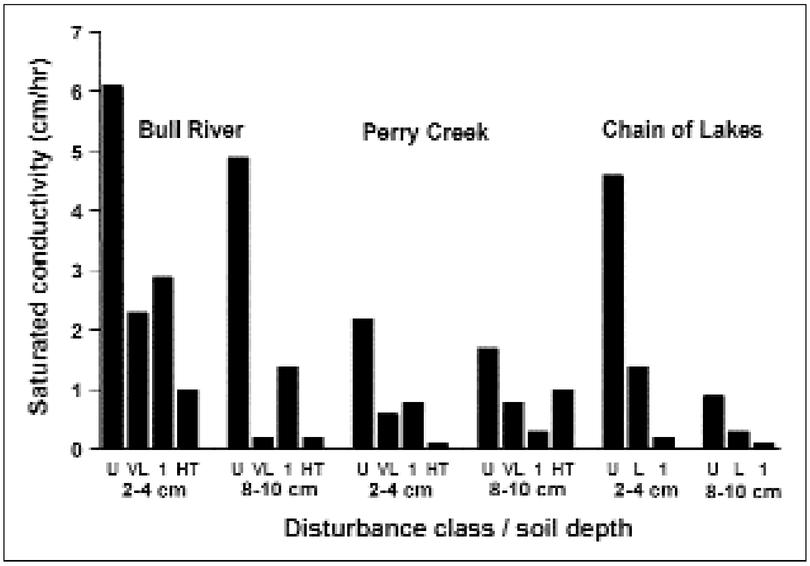

Figure 5—Saturated hydraulic conductivity on soil disturbance types from the mechanized harvesting study shown in Fig. 1 (Curran 1999). (U = undisturbed; VL = light traffic trails; HT = heavy traffic trails – main skid roads; 1 = 5 & 10 cm deep ruts).

Figure 6—Photo of old 1960's era skid trail in the Iron Canyon study site before the recent harvest study. Note lack of tree growth on this trail.

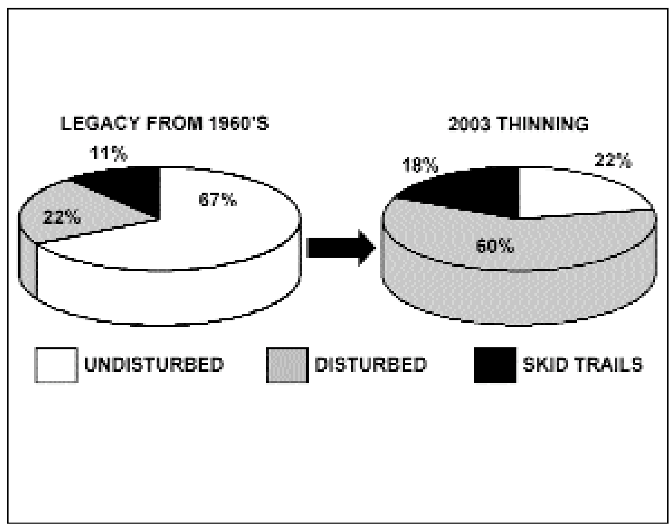

Figure 7—Iron Canyon soil disturbance monitoring pre- and post-harvest showing increase in disturbance following the second harvest entry (Unpublished data on file at the USFS, PSW Research Station, Redding, California.)

Effects of soil compaction can persist for decades (Froehlich et al. 1985), so concern about cumulative effects is important when planning harvest activities. Figure 6 shows there are no trees growing in a heavily used skid trail about 40 years following initial logging. Successive harvest entries can add to already existing compaction and displacement. Figure 7 shows changes from pre- to post-harvest for the area shown in fig. 6. Skid trail coverage nearly doubled, general disturbance increased nearly three-fold, and undisturbed ground fell to one-third its previous extent. Lacking careful supervision, cumulative impacts will occur during ground-based operations.

Displacement

Displacement is the removal of mineral topsoil and forest floor layers from tree-growing sites. It is also a result of machine traffic or dragging of logs. Most organic matter and nutrients needed to sustain plant growth are in the developed topsoil, which varies in depth depending on local soil development. Displacement can result in a loss of available nutrients and effective rooting volume. In addition, it can expose subsoils that are less favourable growing sites (e.g., dense or coarse parent materials). Loss of water-holding capacity, exposure of subsurface seepage, increased runoff, and drainage diversion can also occur and affect off-site values as well. Thus, displacing topsoil an appreciable distance may lower site productivity through loss of available nutrients and effective rooting volume. Dyck and Skinner (1990) found that the overall productivity of a plantation where topsoil had been windrowed was only two-thirds that of an adjacent, non-windrowed plantation.

Severity and extent of displacement are also influenced by controlling and manageable factors (modified from Lewis et al. 1989).

Controlling factors include:

- slope,
- topography,
- soil depth, and
- subsoil type.

Manageable factors include:

- amount and extent of excavation,
- machine size/type,
- seasonal soil conditions (wetness, snow, frozen soil), and
- machine operator awareness, training, and skill.

Few hazard or risk (hazard times consequence) rating schemes are available to evaluate soil susceptibility to displacement. Examples that focus on controlling site factors are the B.C. Ministry of Forests soil displacement and forest floor displacement hazard keys (Curran et al. 2000).

Best Management Practices Components: Harvesting Effects on Soils

Careful planning is required to manage effects of harvest activities on soils. Planning should be based on guidelines and standards that limit specific kinds of soil disturbance and reduce potential for cumulative effects on productivity and hydrologic function. Disturbance from in-block disturbance is often regulated based on inherent sensitivity of the site/soil, with corresponding disturbance criteria and limits that are normally set for temporary access and soil disturbance in the area to be reforested. The most manageable factor may be operator training, awareness, and skill. Managing soil disturbance requires the following best management practice (BMP) components:

BMP components include:

1. site characterization,
2. detailed soil inventory,
3. harvesting strategies to meet soil disturbance standards based on the local soil susceptibility to disturbance,
4. considerations for climatic constraints (e.g., wet soils), or opportunities (e.g., snowpack),
5. monitoring of resulting soil disturbance,
6. restorative treatments for disturbance that is either over prescribed limits or preferably, pre-planned for rehabilitation, and
7. communication and information exchange (feedback loops) amongst the various level above, to enable continuous improvement of standards and practices.

Each of these components is discussed below.

Site characterization (1), and soil mapping of the area (2) are done either during the planning phase for the harvest cycle (e.g., methods in British Columbia described in Curran et al. 2000), or as a ground-checked resource inventory of the entire management area (this is more commonly done in the US Pacific Northwest area). With appropriate interpretations, soil mapping alerts harvesters about the amount of care needed to avoid excessive soil disturbance, when to schedule operations, and what portions of an area are most or least operable in wet weather.

Harvesting strategies (3) have been described for meeting soil disturbance standards under site conditions in western Washington and Oregon by Heninger et al. (1997) and for Interior British Columbia by Curran (1999). The objective is to match equipment capabilities to site sensitivity to disturbance, while providing considerations for climatic constraints (4) (e.g., avoiding wet soils), or opportunities (e.g., using a snowpack to reduce compaction and/or displacement).

Monitoring of resulting soil disturbance (5) follows established methods of measuring the occurrence of specific disturbance types along transects. A working group of the NW Forest Soils Council is currently working towards common disturbance criteria to facilitate comparison and exchange of soil disturbance information (Curran et al. in prep.). Classification systems that are considered to meet desirable criteria, including visually identifiable disturbance types, have been successfully used by the British Columbia Ministry of Forests (Forest Practices Code Act 1995) and Weyerhaeuser Company (Scott 2000), and are currently under developmental use in the U.S. Forest Service Region 6 (Pacific Northwest Region). These classification systems are successfully combined in monitoring protocols to determine severity and areal extent of soil disturbance after operational harvesting (B.C. Ministry of Forests 2001, Heninger et al. 2002).

Restorative treatments for disturbance (6) are required either when disturbance levels are over prescribed limits or preferably, in areas that were pre-planned for rehabilitation.

Figure 8—Decompaction of a logging trail before soil replacement during rehabilitation treatment. (Weyerhaeuser example)

Figure 9—Re-spreading slash onto logging trail as final stage of rehabilitation. (Weyerhaeuser example)

On the right sites, and with appropriate technique, rehabilitation can be an economical and environmentally responsible way to achieve logging efficiency without compromising long-term forest productivity or hydrologic function. (In fact, it can be hard to tell a trail or road existed previously without digging in the soil.) Techniques have been described in the literature, and prescribed in standards or policy guidelines (e.g., B.C. Ministry of Forests 1997), field cards and videos (e.g., Curran 1998). Procedures for successful rehabilitation usually involve both construction and deconstruction phases.

Construction usually includes:

- stockpiling of topsoil for later re-spreading,
- construction of the structure involved out of the subsoil.

Drainage control needs to be considered during construction, to control runoff during harvest but also during and after rehabilitation.

Rehabilitation involves:

- removing large cribbed-in (incorporated) woody debris,
- de-compaction through some form of tillage (e.g., Fig. 8),
- replacement of topsoil layers,
- covering with logging slash similar to the surrounding cutblock area (Fig. 9),
- re-vegetation similar to surrounding cutblock area, and
- use of erosion control mulches or seeding if erosion or sedimentation are concerns.

Rehabilitation of disturbed soils can fully restore the growth potential to that of undisturbed soil, provided the rehabilitation activities are done at the right time. However, not all soils, or all soil disturbances, are conducive to rehabilitation. For example, soil rehabilitation resulted in variable effectiveness in ameliorating compacted soils in a study on Vancouver Island (Maynard and Senyk 2004). In deep, well-drained soils, tilling reduced bulk density to below levels of undisturbed soils and in the short-term improved growth. In contrast, under wetter site conditions rehabilitation decreased survival and growth of seedlings. Other examples where rehabilitation is difficult or very costly include wet clayey-textured soils or where extensive rutting covers the entire harvest area. Rehabilitation is best used as a preplanned activity for main trails and other temporary access like spur roads and landings that are not needed until the next harvest cycle.

Communication and information exchange (feedback loops) amongst the various levels above, should enable continuous improvement of standards and practices (7 from list on page 8) and be part of an adaptive management system used by each agency responsible for managing soil disturbance and its effects on site productivity and hydrologic function. Strategic databases are needed where disturbance types are tracked in relation to actual tree growth effects on long-term monitoring and research sites. Components for this process are discussed by Curran et al. (in prep.).

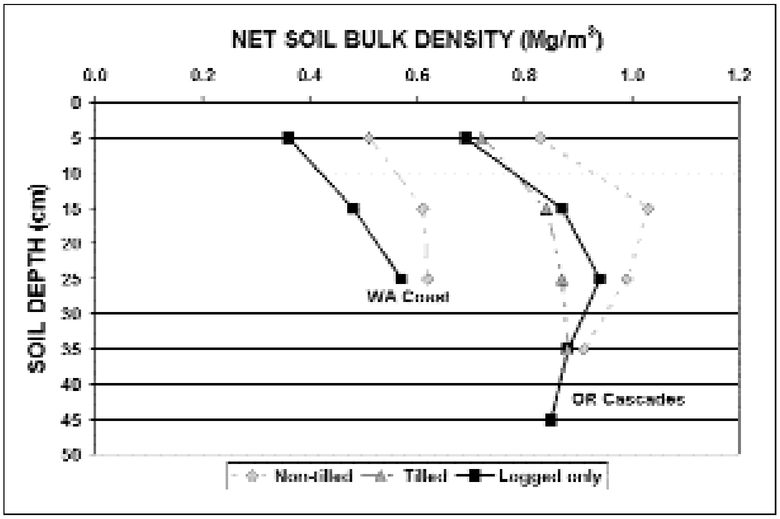

Figure 10—Net soil bulk density (Mg/m^3) for a Weyerhaeuser study of tree growth on tilled and non-tilled logging trails (Heninger et al. 2002)

RESULTING TREE GROWTH EFFECTS

Soil disturbance effects on tree growth depend on the growth-limiting factors influencing trees on a given growing site. Disturbance may both positively or negatively influence a tree's growing environment, with the net result being determined by which factor is most limiting to growth.

Growth limiting factors that are often positively influenced by harvesting soil disturbance include:

- competing vegetation,
- soil moisture,
- soil temperature, and/or
- air temperature (frost).

Growth limiting factors that are often negatively influenced include:

- aeration,
- soil penetration resistance,
- soil moisture availability or storage, and/or
- soil nutrients (e.g., nitrogen falling below critical thresholds).

Tree growth effects reflect the tremendous variability of climates and growing sites in the Pacific Northwest and it can be difficult to draw strong conclusions regarding specific types and severity of soil disturbances and tree growth. It is often necessary to monitor sites across the range of management and environmental conditions, and document results in a database used to continually improve guidelines, standards and management practices. Some examples are presented below to illustrate the above statements.

In a Weyerhaeuser study comparing tilled and non-tilled skid trails, bulk density for logged-only, non-tilled, and tilled skid trails by depth and areas (Washington and Oregon) are plotted in figure 10 (Miller et al. 1996 and Heninger et al. 2002). Compared to the logged-only plots, the non-tilled skid trails showed increased bulk density at both geographic locations. The Oregon Cascades tilled skid trails were rehabilitated to almost the same bulk density as the logged-only control for that area. Thus, tillage recovered the bulk density to that of undisturbed soil. There are significant differences between locations in undisturbed soil bulk densities. The next question would be: does this affect tree growth?

In the Washington study, there were no significant differences in Douglas-fir heights among any of the disturbance classes from year 2 through 18 (Fig. 11) (Miller et al. 1996). In the Oregon study, Douglas-fir (Heninger et al. 2002), height growth was reduced on OR skid trails for about 7 years after planting (Fig. 12). Up to age 7 years, the total heights were diverging between treatments. Seedlings on the non-tilled skid trails averaged 15% less in total height. Height growth (slope of line) from year 7 through 10, showed fairly consistent growth rate among the treatments, and was non-significant. Trees on non-tilled skid trail ruts were always shorter than those on logged-only control plots. Trees on tilled skid trails averaged 2% taller than those on logged-only plots. Thus, soil productivity, as measured by total tree height was recovered by tillage. Working through the data, considering time to attain 1.4-m breast height: LO = 4.0 years; NR = 4.7 years; an average difference of 0.7 years to attain breast height. Therefore, trees on the non-tilled skid trails are about one year behind in total height

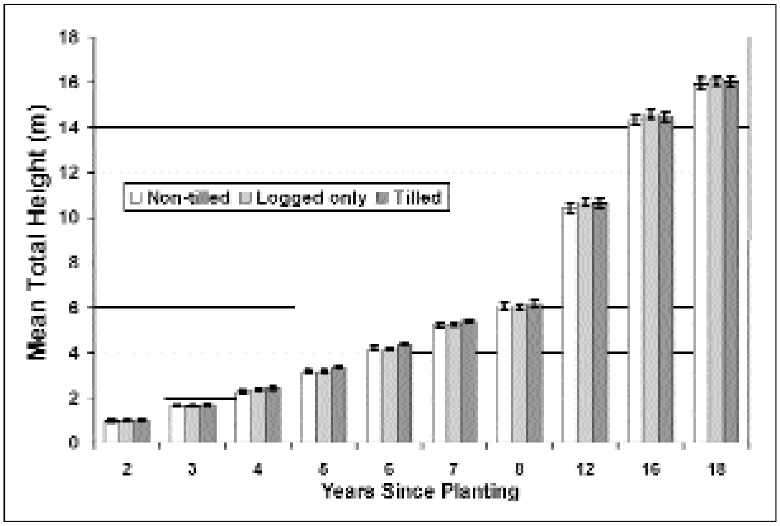

Figure 11—Mean total height of Douglas-fir in Washington for the Weyerhaeuser study of tree growth on till and non-tilled logging trails (Miller et al. 1996).

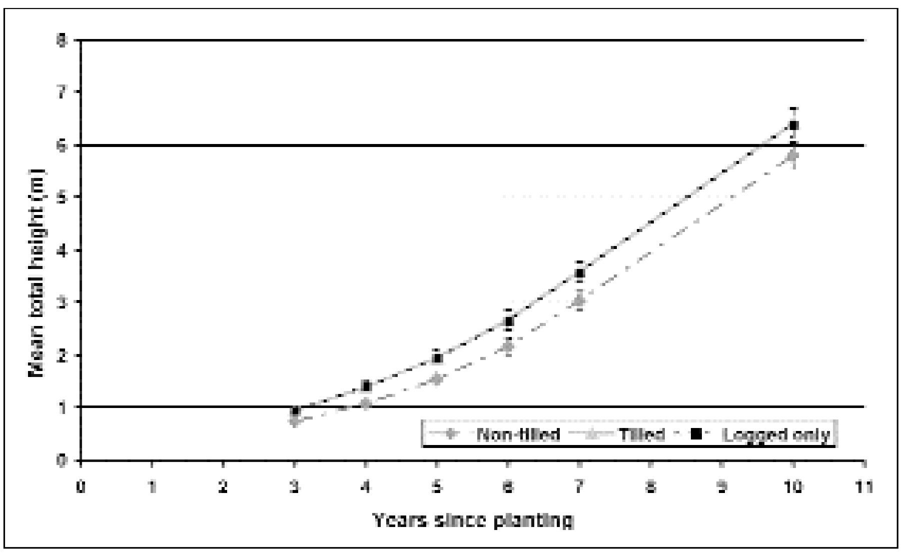

Figure 12—Mean total height of Douglas-fir in Oregon for the Weyerhaeuser study of tree growth on tilled and non-tilled logging trails (Heninger et al. 2002).

and diameter, because it took them one extra year to attain breast height. This difference has been maintained through age 10. The Oregon site has a finer-textured soil than the Washington site and has a longer summer dry period (the effect of the summer dry period is exacerbated by soil compaction). Our hypothesis is that the roots have grown through the compacted skid trail ruts, and are now growing in non-disturbed soil, thus growth rates are now equal. However, the full extent of the impacts on site productivity will surely be magnified if the area in skid trails increases appreciably. Absolute growth will be depressed if roots have little access to friable soil. So, we need to question how common this trend is and hence whether disturbance criteria need to be modified if longer-term data confirms these apparent trends on these site conditions.

LONG-TERM PRODUCTIVITY

Factors that limit early tree growth and establishment are often different from those that influence long-term productivity. Changes occur as a stand grows and matures, particularly around the time of canopy closure, when the

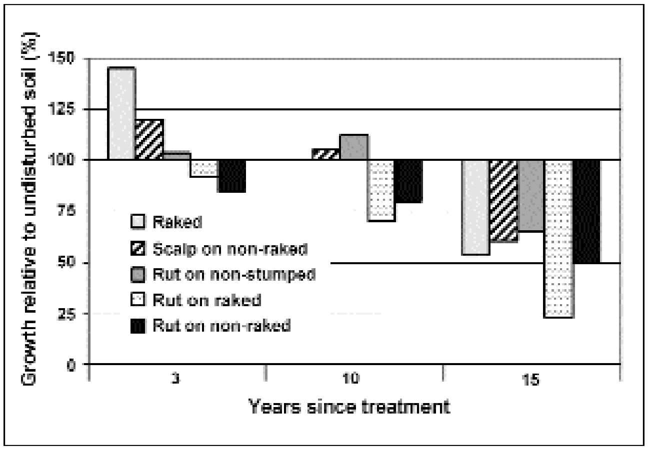

Figure 13—Comparison of relative growth of Douglas-fir on a stump removal trial in southern British Columbia at 3, 10 and 15 years since treatment. All data is relative to the undisturbed condition (adapted from Wass and Senyk 1999.

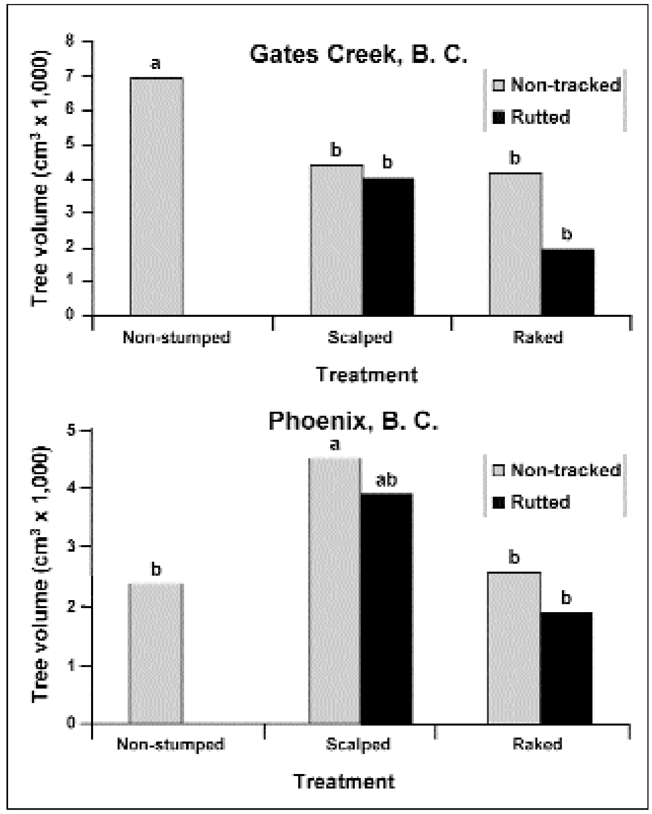

Figure 14—Fifteen-year volume of Douglas-fir seedlings growing in different disturbance types on the Canadian Forest Service Gates Creek and Phoenix stumping trial sites in southern B.C., which are gravelly sandy loam textured with 12% clay at Gates Creek and 4% clay at Phoenix (adapted from Wass and Senyk 1999).

trees are influenced less by microclimate and competing vegetation, and more by regional climatic conditions and a site's ability to provide adequate nutrients and moisture. Effects that are initially positive or negative may reverse over time. The time required to verify long-term effects on productivity is probably longer in slower growing subalpine or droughty areas. For example, on a relatively clayey site in southeastern British Columbia, short-term growth was enhanced on some disturbance types (Fig. 13). However, in the longer-term (15 years), tree growth was poorer on all soil disturbances compared to the undisturbed areas (Wass and Senyk 1999). It is clear that validation takes time and long-term monitoring/data is essential.

Some trends are becoming apparent. Deeply developed soils in humid climates appear to be less sensitive to disturbance whereas shallow, often younger and drier soils are more sensitive. Volcanic ash-influenced soils are often c o nsidered less sensitive than other soils, but data are still forthcoming.

The actual effects of site disturbances on tree growth depend on many factors, like texture. In British Columbia, our longer-term data currently available are from older studies such as that discussed for figure 13. Figure 14 contrasts 15-year Douglas-fir volume on the Gates Creek site shown in Figure 13 with a less clayey site at Phoenix. Both sites have sandy-loam textures, but clay content varies from 4% at Phoenix to 12% at Gates Creek. This also demonstrates the need for a database that covers the specific soils within the operating area covered by the guidelines. In our example, current compaction hazard ratings for the two sites would be the same, but the soils clearly behaved differently.

Figure 15 shows the importance of texture in the results from the Long-term Soil Productivity (LTSP) sites in California. In the clayey and loam textured study sites there is clearly a negative affect of compaction on 10-year biomass, whereas on the sandy sites there is actually a positive effect. This is considered to be due to compaction increasing the water-holding capacity on the sandy sites. Ten-year findings from the oldest LTSP sites in California, Idaho, the Lake States, and the Southern Coastal Plain support the conclusion that impacts of soil compaction on tree growth depend mainly on soil texture and degree of soil drought (Powers et al., in prep.). Studies like the LTSP are producing more long-term data every year. Over time, we will have indicators of soil disturbance conditions that affect tree growth under specific conditions.

Long-term productivity is dependent on the amount of permanent access and the net effect of in-block disturbance on future yield. Timber supply modeling takes into account these two factors. However, we need to improve data upon

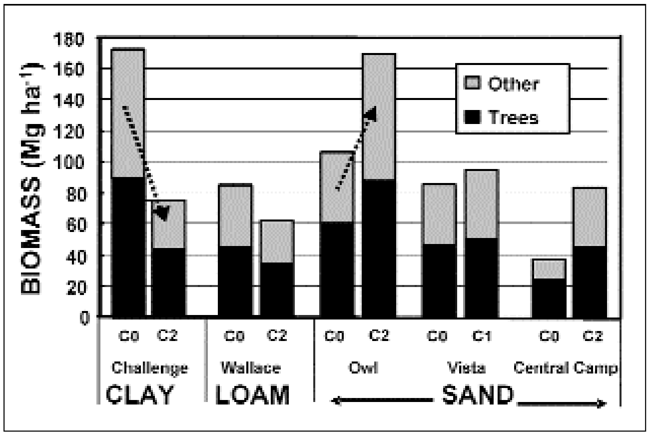

Figure 15—The importance of texture on the LTSP sites in California (C0 = no compaction, C1 = moderate compaction, C2 = severe compaction) (Powers et al. in review).

which in-block soil disturbance projections are based. Many tree growth studies are based on individual tree data from specific disturbance types. Data are needed on an areal (or extent) basis across a cut-block to fully integrate the net effect of on-site disturbance. The LTSP study is an area-based controlled experiment on compaction and organic matter levels that ideally should be paired with operational disturbance types and rehabilitation at each installation. Powers et al. (1998) proposed operationally feasible soil-based indicators for weighing the likely impacts of management on potential site productivity. Among their recommendations were to develop: soil maps highlighting soil types apt to be sensitive to disturbances, soil physical indic a t o r s such as resistance to penetration, and chemical/microbial indicators of nutrient supply, such as mineralizable nitrogen. These indicators need testing and implementation through continued testing, refinement and augmentation of existing soil disturbance standards.

SUMMARY

Harvesting Effects on Soils

Most soil disturbance caused by machine traffic is in the form of compaction and displacement. Compaction often results in increase in bulk density and decreases in penetrability, amount and size of pore space, aeration porosity, infiltration, and hydrologic conductivity. Displacement often results in loss of topsoil and exposure of subsoils. Off-site effects from soil disturbance can include erosion, sediment delivery and loss of life and property loss (not discussed in detail in this paper).

Effects on Tree Growth

Soil disturbance effects on tree growth depend on the nature of the disturbance in relation to the inherent site conditions/sensitivity such as soil texture and climate. Results can range from positive, through no-effect to negative, depending on which growth-limiting factor is affected.

Effects on Long-Term Productivity

Growth-limiting factors change as a stand ages and crown closure occurs. Early effects may reverse over time. Studies like the LTSP will permit better prediction of long-term effects and development of indicators that can be used in managing disturbance at the time of harvesting.

Best Management Practices

A number of soil considerations are required in harvest planning. An adaptive management approach needed to continually improve understanding of management effects on our soils. One needs to:

1. Know the soils upon which operations are planned (through survey of site information),
2. Know what practices should be planned (organize this knowledge based on a soil disturbance classifica tion, and a soil risk rating system),
3. Understand potential effects of these practices (both on- and off-site), and
4. Adapt planned practices (BMPs) over time as more knowledge becomes available.

Site-specific knowledge needs to be part of an adaptive management process for continual improvement of practices (sustainability). A lack of data often results in more restrictive policies, erring on the conservative side. Overly conservative policies and practices cost in terms of economics and social benefit from the forest resource. Conversely, policies that are not conservative enough may cost us in terms of environmental values and long-term productivity and hydrologic function. We need to constantly refine and adapt our guidelines, standards, practices and tools as more information becomes available. To meet these needs, linked databases that track the results of implementation, effectiveness, and validation monitoring are essential.

ACKNOWLEDGEMENTS

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HARVEST PLANNING TO SUSTAIN VALUE ALONG THE FOREST-TO-MILL SUPPLY CHAIN

Glen Murphy and Paul W. Adams[1]

ABSTRACT

During the relatively few days it takes to harvest a stand of trees in a forest, more cost is incurred, more revenue is earned, and potentially greater environmental impacts occur than in all of its prior decades of management combined. Careful design, management and follow-up of the harvesting operation can help to maximize current net revenues (gross revenues minus costs) while protecting future timber productivity.

Net-value recovery from a given piece of land is a function of volume, gross value and costs. These can be affected by a wide range of factors that relate to stand, terrain, markets, company policies, harvest systems, operating conditions and practices, etc.

Harvest planning is a design process aimed at matching equipment and crew capabilities to the operating environment while meeting production goals–one solution does not fit all design situations. To do this effectively the planner needs information on such factors as topography, soil characteristics, tree characteristics, and areas to be preserved/protected. The planner can specify such things as equipment selection, skid-trail layout, felling patterns, operating season, road spacing, harvest opening size, utilization level, duff and slash management, delimbing/processing location, log suspension, post-harvest treatments, and standing tree protection.

To effectively protect or enhance future productivity, a forest manager has to continuously improve current harvesting practices based on lessons learned from monitoring the effects of past practices—sometimes over long periods. Where possible, the effects should be measured directly rather than indirectly, e.g., monitoring not only the soil disturbance but also its effect on tree volume and quality. Such observations are likely to show that not all disturbance and soil changes from harvest operations are equal in their effects on site productivity and net value recovery, i.e., they can range from negative to insignificant to positive.

KEYWORDS: Harvesting, value recovery, soil disturbance, costs, productivity.

INTRODUCTION

Forest managers spend decades creating potential value in each tree. At harvest time more costs are incurred, more revenue is generated, and more environmental impacts can occur than at any other time during the rotation. An important challenge for the harvest planner is to maximize current net value recovery, while sustaining future net value recovery. We prefer to use net value recovery, rather than productivity, as a performance measure in this paper since it ties together the impacts of harvesting and management activities on volume production, values and costs.

*Net value recovery = Volume * (Gross Value – Costs)*

Between seedling and sawmill, there are many ways in which net-value recovery can be sustained or lost along the

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forest-to-mill supply chain. Value recovery can be maximized through:

- improved inventory systems which allow better understanding of the resource in terms of quantity, quality and location,
- optimal scheduling of stands and allocation of logs to markets,
- planning of harvest layout,
- selection and scheduling of appropriate equipment and practices,
- improved log segregation and processing practices,
- optimal truck scheduling and log stocks management,
- improved process manufacturing, and
- improved post-harvest monitoring and treatment.

In this paper we will briefly look at: is there a need for harvest planning in the Pacific Northwest (PNW), what factors affect gross value recovery and harvesting costs, what is harvest planning, what information is needed, what can the planner specify, and finally the importance of monitoring performance and continuous improvement.

Is There a Need for Harvest Planning?

Good harvest planning generally leads to greater productivity, reduced costs, improved worker safety, and fewer environmental impacts.

Today, many forest companies, including those in the PNW, operate in a worldwide marketplace facing increasing global competition from other timber producers. Competition is coming, however, not only from other wood producers but also from (1) other industries, such as steel, aluminum, plastics, and composites that are competing successfully with the forest industry in traditional markets, and (2) alternative uses for the investors' dollars. To be globally competitive, forest companies need to control costs, sort and allocate logs to the most appropriate markets, and maximize the value of the forest at the time of harvest. Harvest planning is vital for meeting these economic requirements in the short and long term.

Forest soil compaction has been studied for over 50 years in the PNW (Garrison and Rummel 1951). It has been found that most PNW soils are susceptible to compaction, compaction occurs in both dry and moist soils, large areas may be compacted, and compaction can persist for decades (Wronski and Murphy 1994). Soil compaction sometimes, but not always, leads to reduced tree growth, and effects may vary with soil type and other site conditions. For example, a study of compaction effects on seedling growth on three sites in northern California with clay, loam, and sandy loam soils found reduced, insignificant, and increased stem volume growth, respectively (Gomez et al. 2002). Causal factors for observed growth impacts have become clearer, e.g., Powers et al. (1998) found that sandy loam soils compacted by mechanized thinning had soil strengths that were limiting to root growth during the summer months. They conclude that such a seasonal soil strength increase may effectively shorten the growing period for impacted trees.

PNW forest managers are not alone in their interest in the impacts of harvesting systems on the site. Research on the impacts of soil disturbance on tree growth in radiata pine plantations at four sites, with different soil characteristics, in New Zealand has shown that planted seedling survival was not affected, stem malformation was affected on two of the sites, and selection for pruning and for final crop was affected on all four sites. Volume growth was also affected, particularly for the heavily disturbed areas (Firth and Murphy 1989, Murphy and Firth 2004). Other New Zealand research has shown that, while the impacts of heavy soil disturbance (topsoil removal and subsoil compaction) on volume production may be large (e.g., up to a 40% reduction) the impacts on net value recovery are likely to be even greater (e.g., up to 65% reduction) due to stems having to be cut into lower value products because of size and quality constraints (Murphy et al. 2004).

Even without planning, harvesting operations create a mosaic of disturbance classes so these volume and value reductions are not seen over the whole harvest site. However, harvest planning can effectively reduce the impacts that do occur. Moreover, economic analyses have shown that volume losses from compaction can justify a significant investment in planning and other measures to avoid or reduce these impacts (Stewart et al. 1988, Murphy et al. 2004).

Factors Affecting Gross Value Recovery

Many factors affect the gross value recovery coming off a given piece of land (Murphy et al. 1991, Conradie et al. 2004). These include among other things:

- the proportion of the land area allocated to timber production—land allocated to non-timber uses, such as reserves, is likely to reduce gross value recovery
- the volume per hectare of productive area and the tree species planted on that area
- the tree size—usually, though not always, larger trees are more valuable than smaller trees both on a per tree basis and a unit volume basis
- the quality of the wood and the treatments the stand has undergone—stems with rot or malformation are less valuable than well formed, rot-free stems; pruned

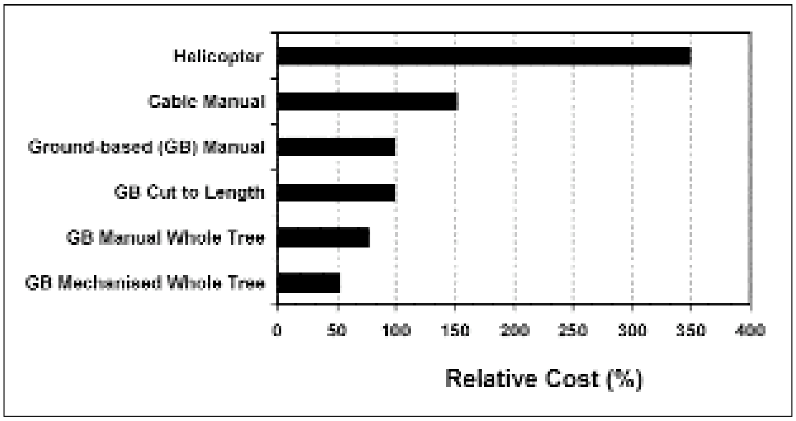

Figure 1—Standing-tree-to-truck costs for a range of harvesting systems (costs are expressed relative to costs of ground-based manual operations).

stems are generally more valuable than unpruned stems; older, high density wood is usually more valuable than young, low density wood, etc.

- the markets available for the wood, the prices the markets are prepared to pay, and how well the wood has been allocated to those markets
- the premium the markets are prepared to pay for "environmentally friendly" products—there are mixed signals from consumers on how large a premium will generally be paid for environmentally friendly products, ranging from nil to less than 10%
- gains or losses in productivity and stem quality due to soil disturbance related to forest operations
- thinning-damage—the few studies that quantify thin ning damage in terms of value recovery indicate that losses range from 1 to 2% of the value of the stand at the time of final harvest
- felling practices—8% to 12% of the value of a stem can be lost through poor manual falling practicesex-traction breakage—up to 1% of the potential value may be lost through extraction breakage
- bucking tools and practices—bucking can have one of the largest impacts on value recovery. Losses of up to 30% of potential value recovery have been recorded for manual operations and up to 70% for mechanized operations.
- loading and transport damage—little research has been done on value recovery losses due to loading and transport. Damage is likely to result in losses of less than 1%. Mis-sorting and loading of logs for the wrong destination sometimes is of bigger concern.
- harvest system selection—mechanized harvesting systems have value recovery advantages over conventional systems with mechanized felling (due to lower stumps and less breakage) but tend to incur lower value recovery during bucking.
- equipment selection—mechanized felling equipment that is too small for the tree size it is operating in can result in unacceptable value losses from stem breakage, and butt damage. Soil disturbance can be high if inappropriate equipment is selected.
- operator skills and training—studies of many types of operations indicate that a third of the variation in performance is often related to the human factor.

Factors Affecting Harvesting Cost

Many factors affect the harvesting costs for timber coming off of a given piece of land (Conway 1976). These include among other things:

- the size of the harvest unit—all harvest units generally incur the same fixed move-in, move-out costs. Unit volume costs are therefore likely to be greater for small harvest units than large harvest units.
- harvest system selection (see Figure 1 for relative costs per unit of volume)
- harvesting equipment selection—even for the same harvesting system, differences in costs can result from the type of equipment selected. Not all equipment has the same features, purchase price, repairs and maintenance requirements, etc.
- piece size—harvesting can generally be classed as a piece handling problem; it takes a similar amount of resources to handle a small piece as it does a big piece. Harvesting small trees, or big trees cut into small pieces, tend to result in higher costs than harvesting bigger trees. Costs rise rapidly once piece size falls below about 1 m^3 (200 bf).
- stand treatment—thinning generally results in higher costs (~ 10%) than clearfelling for the same piece

size. The size of this increase depends largely on the number of stems per hectare removed.
- operating practices—for example, requiring a mechanized harvester to cover forwarder trails with a running bed of limbs and tops may lower harvester productivity and increase costs
- operator skills and training—see comment on value recovery
- terrain and soil type—steep terrain is generally more expensive to harvest than gentle terrain. Some soil types can limit harvesting activity, particularly when they are wet, resulting in a shorter operating season. Fixed costs, therefore, have to be spread across fewer operating days. Some soils can result in significant wear on harvesting equipment, e.g., sands or volcanic ashes.
- weather conditions—can limit the length of the operating season or reduce productivity on days when harvesting can be undertaken.
- extraction distance—generally harvesting costs increase as the distance the timber has to be extracted increases. One of the exceptions to this is for cable logging systems where very short extraction distances can result in frequent shifting of cables and a lot of unproductive time.
- market complexity—the more complex the market (as measured by the number of log sorts) the higher the harvesting cost. This can be due to an increase in time required for sorting, a reduction in average piece size, larger landings required, etc.
- distance to markets—transport from landing to mill can account for up to 50% of stump-to-mill harvesting costs. The greater the distance to the mill, the higher the transport costs.
- environmental protection requirements—such as riparian area protection, use of designated/old skid trails, etc.

What Is Harvest Planning and What Information Is Needed to Implement It?

Harvest planning is a process whereby equipment and crew capabilities are matched to social, environmental and economic requirements so that production goals can be met. One solution does not fit all design situations. As noted earlier, an important goal is to sustain net value recovery along the forest-to-mill supply chain.

Information required by harvest planners to effectively carry out their job includes among other things:

- data on the terrain–contour maps, digital elevation models, aerial photos,
- applicable rules and regulations related to the project area,
- detailed information on existing infrastructure; e.g., road locations and conditions, bridge weight limits, sortyard locations, etc.,
- harvest schedule for area-level tactical planning (e.g., how will this harvest area relate to past and future harvest areas?),
- soils maps and soil descriptions,
- location of problem areas; e.g., unstable slopes,
- special on-and off-site requirements; e.g., archeological sites, riparian zones, reserves, viewsheds,
- inventory data; volume per hectare, tree size and stem characteristics,
- markets; what log grades and lengths are stems likely to be cut into,
- available equipment and skills in the region.

What can the Harvest Planner Specify?

There are many things the harvest planner can specify that will affect soil disturbance and net value recovery. Some of these include:

1. System selection—the selection of the harvesting system can affect costs, gross value recovery, and soil disturbance. A wide range of systems are available—helicopters, single-span skyline, multi-span skyline, skidder logging, excavator logging, cut-to-length systems, motor-manual systems, fully mechanized systems, etc., —but only a limited number of these will result in an economically viable harvest operation for a specific unit.

2. Equipment selection—equipment design, track and wheel size, and suspension type can all effect duff integrity and soil disturbance. Murphy (1982) found that equipment design could cause a two- to three-fold difference in the number of passes made by ground-based extraction equipment before topsoil removal and subsoil compaction occurred on skid trails.

3. Skidtrail layout—planned skid trails can result in less soil disturbance overall, compared with the logger’s choice of travel, by designating where ground-based equipment travels (Froehlich et al. 1981). Providing the distance between skid trails is not too great (requiring large amounts of time to pull winch-line to hook on the logs), costs can also be reduced because of faster travel times from stump to landings.

4. Felling pattern—timber felling patterns can influence the degree of soil disturbance generated, and the amount of breakage and damage to the residual crop. Felling stems

parallel to each other, and in a herring-bone pattern in relation to the extraction skid trail or skyline corridor, helps to minimize disturbance, breakage and damage (Garland 1983, Garland and Jackson 1997).

5. Operating season—limiting the operating season to times when the soils are less susceptible to disturbance may reduce the impacts of harvesting on future site productivity. Identifying effective limits is challenging, however, given the wide range of site conditions and soil and machine types that exist. For example, loaded machines and travel on slopes can result in much greater vehicle ground pressures than the static values more often reported (Lysne and Burditt 1983). Limiting the operating season will also result in higher harvesting costs as fixed costs have to be spread across fewer operating days and harvest volume production.

6. Road and landing location and spacing—as well as taking land out of productive use for timber production, forest roads and skid trails can be important sources of runoff and sediment. However, only a fraction of all roads and skid trails usually cause problems. Some of the key factors determining whether they are a problem are their length, location, design, use and maintenance history. Road spacing can also affect harvesting system selection, harvesting productivity (closer road spacings usually result in faster cycle times and lower extraction costs), and road construction costs (Sessions 1992).

7. Utilization level (bole-only or full-tree) and processing location—short-term net value recovery can be increased (or decreased) by increasing the level of biomass utilization (Murphy et al. 2003). Nutrient removal from the site, however, may or may not have significant impacts on long-term value recovery. Processing stems at the stump versus at roadside can have different effects on costs, value recovery, and nutrient concentration. (Murphy 1987, Smidt and Blinn 1995).

8. Standing tree protection—damage to standing trees during thinning operations can result in future gross value losses due to reduced growth and quality impacts (e.g., scarring) (Han et al. 2000). The potential for damage can be greater near designated skid trails and skyline corridors where traffic flow is concentrated. Providing protection for standing trees comes at a cost but may result in net value recovery gains.

9. Duff and slash management—delimbing at the stump keeps nutrient resources dispersed. Slash on skid trails acts as a cushion between heavy equipment and the soil. Maintaining or increasing slash on skid trails has been shown to help reduce compaction and disturbance (Allen et al. 1997).

10. Log suspension—harvesting operations can be designed to reduce soil disturbance by providing greater log lift. However, this sometimes has a negative impact on costs and gross value recovery. Log suspension can be achieved by providing greater lift (e.g., using helicopters, multi-span systems, forwarders instead of skidders, etc.) or by cutting the stem into shorter logs.

11. Post-harvest treatments—runoff and erosion can be minimized by including water bars, or slash-filter and sediment traps in the design of skid trails and roads. Limbs and tops, removed at the landing, can be spread out over the harvest unit.

12. Riparian area protection—delineation of riparian areas can affect harvest system productivity, costs and net value recovery as well as the amount of sediment reaching streams.

13. Tillage of skid trails and large landings—is useful for clearfell sites when compaction is unavoidable; tillage of thinned sites may result in damage to the root system of the residual crop, but the impact of such damage has not been widely studied. Various implements have been used for tilling compacted forest soils, and cost-effectiveness can vary significantly (Andrus and Froehlich 1983). Where moisture is limiting, the tree productivity benefits of tillage may be masked by lack of weed control. Tillage can also be extended to treat areas compacted by earlier machine operations.

Continuous Improvement and Monitoring

To effectively protect or enhance future productivity and net value recovery, a forest manager has to continuously improve current harvesting practices based on lessons learned from monitoring the effects of past practices—sometimes over long periods. For example, until quite recently it was thought that soil compaction was invariably bad and was a problem serious enough to merit major operational changes.

Where possible, the effects of harvesting practices should be measured directly rather than indirectly; a detailed study of the soil is not always needed to identify soil productivity concerns. Soil productivity is reflected directly in tree growth, form and health. When coupled with indirect monitoring of soil productivity (mapping and quantifying the problem visually, with bulk density measurements, with penetrometers, etc.), a much clearer picture of cause and effect relationships and the situations that merit attention should emerge.

CONCLUSIONS

The impacts of soil disturbance on volume production can range from negative to insignificant to positive. Productivity measures, however, need to include a quality component and be long-term. Net value recovery is a useful alternative performance measure to productivity.

Sustaining net value recovery along the forest to mill supply chain means managing activities that affect not only productivity (i.e. volume production) but also gross value recovery and costs. To sustain net value recovery, future impacts as well as current impacts need to be considered when harvesting operations are being planned. Harvest planners have a wide range of alternative solutions at their disposal. One solution does not fit all design situations.

Forest managers looking to continuously improve their practices, and their net value recovery, need to manage gross value recovery and costs associated with their operations. They also need to monitor and evaluate the impacts of c u rrent operations on the trees, in addition to the soils.

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STAND ESTABLISHMENT

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SILVICULTURAL TECHNOLOGY AND APPLICATIONS FOR FOREST PLANTATION ESTABLISHMENT WEST OF THE CASCADE CREST

Timothy B. Harrington[1] and Jeff Madsen[2]

ABSTRACT

Research and operational trials have identified methods of forest plantation establishment that promote high rates of survival and early growth of tree seedlings in the Pacific Northwest. Primary reasons for this success are the intensive control of competing vegetation provided by herbicide treatments and the planting of high quality seedlings. This paper discusses the current state of the art in forest plantation establishment in Oregon and Washington west of the crest of the Cascade Range. It considers technologies developed in the last two decades that currently have widespread application on lands managed primarily for wood products. The focus of this review is on even-aged silviculture of conifer seedlings, especially coastal Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*), but other species, silvicultural systems, and regions are considered where appropriate.

KEYWORDS: Vegetation management, nursery technology, tree planting, Douglas-fir.

BACKGROUND

In western Oregon and Washington (i.e., the "Westside"), nearly half of all timberland is publicly owned. The federal government owns 38% and state agencies control 11% of all timberland in this region. Remaining ownership is dominated by industrial (34%) and other private landowners (17%), including various tribal ownerships (Bolsinger et al. 1997, Alig et al. 2003, Haynes 2003, Campbell et al. 2004). Each of these landowner classes differs strongly in their management philosophies and constraints. In the last decade, federal forestry agencies have had to operate within a litigious environment, and as a result, their timber harvest currently is focused on salvage from fire and insect disturbances (Malmsheimer et al. 2004). State-managed forest lands work under a range of constraints and objectives including those of a federal Habitat Conservation Plan for lands of the Washington State Department of Natural Resources, various land trust concerns, and economic mandates (Coyner and Coyner 2004, OSDF 2004a, Washington DNR 2004). With the exception of tribal owners, private landowners operate under state Forest Practices Laws, the federal Clean Water Act, and the Endangered Species Act. The Sustainable Forestry Initiative includes additional self-imposed regulations by forest industry (SFB 2004). As a result of these various conditions and constraints, most of the timber harvest on the Westside comes from private land (87%). Only 2% of the harvest comes from federal lands with the remaining 11% from state-managed timberlands (Larsen and Nguyen 2004, OSDF 2004b).

The private forest industry faces increasing regulatory restrictions as urban and suburban interfaces move ever closer to its land. Increasing property values from real estate development are shifting land investment away from traditional forestry practices in some areas (Alig et al. 2003). Facing global competition for wood products, Westside industrial landowners are pushed towards intensive silviculture and lower rotation ages as they continue to protect public resources and control treatment costs (Talbert 2004).

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PREDOMINANT LIMITING FACTORS

Much of the forest land on the Westside is classified as the Western Hemlock (*Tsuga heterophylla* (Raf.) Sarg.) Zone because of the species' potential to establish and ultimately dominate most forest plant communities (Franklin and Dyrness 1973). Douglas-fir is the primary crop species, with occasional planting of western hemlock, western redcedar (*Thuja plicata* Donn ex D. Don), and red alder (*Alnus rubra* Bong.) (Briggs and Trobaugh 2001). Forest site quality is determined largely by soil depth, soil texture and rainfall (Steinbrenner 1981). Nitrogen is the macronutrient most limiting to forest productivity (Heilman 1981).

Douglas-fir seedlings require moderate to high levels of sunlight for optimal development. Mailly and Kimmins (1977) found that seedlings need at least 40% of full sunlight to ensure survival and continued morphological development, although maximum growth rate occurs under full sunlight conditions (Drever and Lertzman 2001). In contrast, western redcedar seedlings require only 10% of full sunlight to survive (Wang et al. 1994), and their maximum growth rate occurs at 30% of full sunlight (Drever and Lertzman 2001).

Experiments throughout the region testing two-aged and uneven-aged silvicultural systems have identified significant reductions in conifer seedling growth from overstory shade and other resource limitations (Brandeis et al. 2001, Mitchell 2001, York et al. 2004). Such multi-cohort methods of regeneration can be challenging to establish and maintain; thus, most of the wood-producing industrial forests on the Westside are managed using even-aged silvicultural systems with clearcutting the dominant method of regeneration (Smith et al. 1997).

Competing Vegetation

Perhaps the most important biological constraint to establishment of Westside forest plantations is competition for limited resources from competing vegetation. Intense shade and early-season depletion of soil moisture occur when development of competing vegetation goes unchecked. For at least five decades, forest managers have been aware of the competitive pressure that results from tall-growing hardwoods and shrubs. Reductions in Douglas-fir height growth have been directly related to the amount of shade at or above half of the tree's height (Ruth 1956, Howard and Newton 1984, Wagner and Radosevich 1991a). In addition, severe competition for soil water can result from as little as 20% crown cover of woody vegetation (Oliver 1984, Shainsky and Radosevich 1986, White and Newton 1989).

About fifteen years ago, Westside foresters became keenly aware of the importance of competition from herbaceous vegetation (Newton and Preest 1988, Petersen et al. 1988, White and Newton 1989, Hughes et al. 1990, Wagner 2000). Many of the common grass and forb competitors invade recently harvested sites by wind dispersed seed. During the first three years of plantation establishment they compete strongly with conifer seedlings for soil water, sometimes depleting available supplies early in the growing season (Newton and Preest 1988).

Invasive species of all types are a continual threat to ecosystems throughout the United States (National Biological Information Infrastructure 2004). Recent changes in Westside plant communities resulting from invasion by non-native species may intensify the competitive pressure that already exists for conifer seedlings during plantation establishment. Species such as Scotch broom (*Cytisus scoparius* (L.) Link.), Himalayan blackberry (*Rubus discolor* Weihe & Nees), and Japanese knotweed (*Polygonum cuspidatum* Sieb. & Zucc.) establish soon after a site disturbance such as clearcutting. Once established, their seed or bud banks can survive for extended periods of time, making them long-term residents of Westside forest communities. Other species, such as English holly (*Ilex aquifolium* L.), English ivy (*Hedera helix* L.), and false-brome (*Brachypodium sylvaticum* (Huds.) Beauv.), are shade tolerant and capable of establishing in a wide range of light environments. Thus, they may already be present in a forest community at the time of timber harvest and able to quickly increase their abundance in response to the disturbance.

Wildlife Damage

Damage to conifer seedlings from black-tailed deer (*Odocoileus hemionus columbianus* Richardson), Roosevelt elk (*Cervus canadensis roosevelti* Merriam), and mountain beaver (*Aplodontia rufa pacifica* Merriam) can be particularly devastating during establishment of Westside forests (Black et al. 1979). Their effects on early growth of Douglas-fir seedlings are so significant that often silvicultural studies must be fenced to eliminate confounding of tree responses from animal damage. Western redcedar is particularly vulnerable to browsing by deer and elk because of its high palatability, whereas western hemlock is generally avoided. Brandeis et al. (2002) found that, when browsed for three consecutive years, cedar had only 56% of the stem volume of non-browsed seedlings

Root and Foliage Pathogens

The common root disease of Westside forests, laminated root rot (*Phellinus weirii* (Murr.) Gilb.), is generally considered a site-specific problem that impacts yield but does not destroy entire stands (Thies and Sturrock 1995). Since 1990, the foliage disease, Swiss needle cast (*Phaeocryptopus gaeumannii*), has reached epidemic status and caused significant growth losses in coastal Douglas-fir (Maguire et al. 2002). However, recent aerial surveys suggest that the Swiss needle cast epidemic may be stabilizing or even subsiding (Kanaskie et al. 2004). Sudden oak death (*Phytophthora ramorum*) is a potential future threat to forest stands because of its wide variety of plant hosts and ability to invade through either the stem or foliage, depending on the host.

Environmental Regulations

Although these biological constraints can pose some unique challenges to plantation establishment, often the overriding constraints to management activities are environmental regulations imposed by government agencies or self-imposed by forest industry. National and state environmental protection laws impact reforestation activities significantly. In addition, a relatively recent development in forest management is the emergence of an activist citizenry that has the time and resources to challenge specific management activities of public and private landowners. National Forests are often involved in years of administrative appeals prior to final adoption of management plans (Teich et al. 2004; Malmsheimer et al. 2004). These laws and/or social pressures can directly influence the entire range of forest management activities.

For example, new forest practices laws for riparian zones (to safeguard threatened fish species) have significantly increased the area that is non-managed or managed at low intensity. Adjacency constraints in the Sustainable Forestry Initiative and state Forest Practices Laws can determine the location of future timber harvests and even reduce a landowner's planned harvest levels. Adjacency constraints also encourage managers to make large investments in silvicultural treatments to accelerate the development of young stands so they will meet the "green-up" requirements that enable the harvest of an adjacent stand. Air quality ("smoke management") rules have almost eliminated the use of broadcast burning for site preparation on the Westside.

TECHNOLOGY APPLICATIONS

A wide variety of research programs within universities, government laboratories, and private industry have developed successful approaches for regenerating Westside forests given the challenges posed by competing vegetation, animal damage, and pathogens. These techniques are contributing to an ever-increasing intensity of silviculture that accelerates the rate at which forest plantations become merchantable.

Vegetation Management

A considerable amount of research on plantation establishment has contributed to a conceptual framework of "crop" seedling responses to vegetation management. Many of these concepts have been borrowed from the agricultural literature (Cousens 1987) and applied successfully to forestry. The following are three major contributions to this conceptual framework.

(1) Competition thresholds-(Wagner et al. 1989, Monleon 1999) quantify the "breakpoints" in relationships of crop seedling performance to abundance of competing vegetation. The breakpoints signify large changes in seedling response, and therefore, dictate the abundance at which competing vegetation should be managed to ensure a reasonable return on investment from vegetation management.

(2) Critical-period thresholds-(Wagner et al. 1999, Wagner 2000, McDonald and Fiddler 2001, Rose and Rosner 2004) define the time period when competing vegetation should be controlled (i.e., duration of weed control) in order to prevent reductions in crop seedling performance.

(3) Minimum area of vegetation control-(Dougherty and Lowery 1991, Rose et al. 1999) quantifies the portion of a crop seedling's growing space that must be kept free of competing vegetation to maximize its performance. If the minimum area is less than 100%, a spot treatment can be prescribed that will potentially provide a cost-saving relative to a broadcast treatment.

Intensive control of competing vegetation early in stand establishment is being attempted on some forest sites as a means of maximizing productivity and accelerating the rate of stand development. Larger-scale use of backpack sprayer crews is providing forest managers with the flexibility to conduct vegetation management treatments in local problem areas. Pre-harvest herbicide applications are being used successfully in southwestern Oregon and northwestern California to provide more effective control of evergreen woody vegetation than from conventional post-harvest methods (Fredricksen 2005). While herbicides are a critical tool for Westside plantation establishment, all of the new products now in use have much lower toxicity to mammals and fish compared to older products. In addition, most of the newer products are effective at extremely low application rates (e.g., sulfometuron herbicide typically is applied at 3 ounces or less of active ingredient per acre).

Herbicide technology has improved considerably over the last two decades. Experimental comparisons have demonstrated the effectiveness of thinline applications of imazapyr or triclopyr ester herbicides for controlling bigleaf maple (*Acer macrophyllum* Pursh.), a rapidly growing and difficult-to-control competitor (Wagner and Rogozynski 1994). When added to fall site preparation sprays of imazapyr or glyphosate herbicides, sulfometuron provides effective control of herbaceous vegetation throughout the following growing season (Ketchum et al. 1999), thus, eliminating the need for an additional treatment in the spring. One of the newer herbicides, clopyralid, provides selective control of broadleaf herbs without injuring neighboring Douglas-fir seedlings.

Pre-emergent herbicides have the potential to prevent germination and suppress growth of shrub and hardwood competitors. For example, a greenhouse study demonstrated that hexazinone herbicide reduced germination and suppressed growth of varnishleaf ceanothus (*Ceanothus velutinus* Dougl.), deerbrush ceanothus (*C. integerrimus* H. & A.), and thimbleberry (*Rubus parviflorus* Nutt.) (Rose and Ketchum 2002b). Similarly, hexazinone reduced the survival and growth of seedlings of the invasive shrubs, Scotch broom and Portuguese broom (*Cytisus striatus* Hill) (Ketchum and Rose 2003). Figueroa (1994) found that sulfometuron significantly reduced germination of red alder seedlings.

Non-herbicide methods for controlling competing vegetation also are being developed. After two decades of research on methods for controlling red alder with cutting treatments, Belz (2003) concluded that the greatest mortality occurred when trees were cut at six to seven years of age and 13 to 15 weeks after budbreak, presumably when carbohydrates reserves were at their lowest level. Tappeiner et al. (1996) observed reductions in crown volume and area of bigleaf maple sprout clumps if the parent trees were cut at 1-ft height one or two years before stand harvest. Mulches are being used successfully to both conserve soil water and reduce abundance of competing vegetation adjacent to conifer seedlings (McDonald and Helgerson 1990). Mulching is most effective when the material has high longevity and is applied early in the growing season before soil water has been depleted.

The timing, intensity, and duration of competing vegetation control are essential features to consider for any vegetation management treatment because often they determine treatment cost-effectiveness. Wagner et al. (1999) found that the duration of vegetation control resulting in a continued increase in stem volume index varied among conifer species from two to four years. Manually removing competing vegetation around ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) seedlings provided similar tree growth responses regardless of whether the treatment occurred in years 1-3, years 4-6, or years 1-6 after planting (McDonald and Fiddler 2001). Ten-year growth of Douglas-fir was similar when grown with densities of varnishleaf ceanothus of 0 to 2700 plants/acre, but it decreased by 41% when density exceeded 6070 plants/acre (Monleon et al. 1999). However, regardless of ceanothus density, Douglas-fir growth increased following removal of herbaceous vegetation. Rose et al. (1999) found that Douglas-fir growth increased with area of vegetation control, with maximum values occurring when either 60% (one site) or 100% (two sites) of growing space was treated. Reporting on a large study that compared various levels of vegetation control in western Oregon, Rose and Rosner (2004) found that increases in stem volume were proportional to the total number of years of control for all four conifer species tested. Seedling growth after four years of control resulted in 3- to 18-fold increases in stem volume relative to non-treated seedlings.

Seedling Quality

Quality of Douglas-fir planting stock has improved greatly in the last two decades. These improvements have been prompted by studies attesting to the benefits of large planting stock (Wagner and Radosevich 1991b, Roth and Newton 1996, Rose and Ketchum 2003). In addition, the "target seedling concept," which links specific morphological and physiological traits with field performance, has improved methods of plantation establishment by defining tangible seedling characteristics for nursery managers to cultivate and for foresters to select (Rose et al. 1990). The plug+1 and 1+1 bareroot stock-types are currently accepted standards for plantation establishment on the Westside and have replaced the mainstay of the 1980's, the 2+0 bare root. Exponential nutrient loading is a relatively new concept for nursery fertilization regimes (Timmer 1996) in which fertilizer is applied at an exponentially increasing rate to maintain seedling nutrient content at a constant level, and therefore free from nutrient stress. This approach has been used effectively in forest productivity research to test the upper limit of tree growth responses to fertilization (Powers and Reynolds 1999).

Planting Techniques

Given the current focus on large seedlings, planting is almost entirely done with a planting shovel, replacing the former planting tool of choice, the hoedad. The shovel enables planters to set the roots of large stocktypes in a hole of adequate width and depth, thereby avoiding potential problems associated with shallow planting and deformity of the taproot. Although use of careful planting methods continues to be recommended, (Rose and Morgan 2000), taproot deformity at planting may not cause significant problems to the developing plantation. Surprisingly, Haase et al. (1993) did not find any differences in 10-year survival and growth of Douglas-fir seedlings planted with straight, "L"-shaped, or "J"-shaped root systems. Planting in the fall, as opposed to the winter or early spring, has been used in coastal areas to take advantage of warm soil temperatures in the fall that should translate into increased root growth following planting; however, the authors are not aware of any published research on the benefits of this practice.

Planting Density

Although planting density continues to be an item of debate, most plantations are established at 400 to 500 seedlings/acre. Recent research has indicated that higher planting densities (up to 1200 trees/ac) may stimulate short-term increases in both diameter and height growth of Douglas-fir (Scott et al. 1998; Flewelling et al. 2001). This effect may be the result of a phytochrome response that modifies seedling allometry (Ritchie 1997). Because the growth stimulation associated with high initial densities is relatively short-lived, and reverses after several years, pre-commercial thinning must follow soon thereafter if potential benefits are to be captured. It remains to be seen if these early growth gains due to higher initial densities justify the cost of planting more trees per acre and the need for early pre-commercial thinning.

Genetic Improvement

Possibly more resources have been directed towards genetic improvement of conifers on the Westside than any other yield-improvement treatment. Regional tree improvement cooperatives are now well into second generation testing and breeding efforts. Nearly all large private landowners and some public agencies utilize various levels of genetically improved seed in their regeneration efforts. A recent realized genetic gain study in Oregon estimated a 28% stem volume gain for Douglas-fir (St. Clair et al. 2004). Greater genetic gains than this may be achievable with increased selection differentials (Jayawickrama and Ye 2004). Current programs select for wood quality and stem form factors in addition to increased growth rates. Although the genetic source of seedlings can significantly contribute to stand productivity, research on ponderosa pine indicates this may only happen when they are grown without competing vegetation (McDonald et al. 1999). In the absence of competing vegetation, full-sibling families averaged 1.3 ft taller than "woods-run" families six years after planting; whereas, their heights were not significantly different in the presence of competing vegetation.

Seedling Fertilization

Seedling fertilization is being considered as a technique for accelerating juvenile growth of Douglas-fir. New, slow-release products have been developed that can be combined with the soil medium of container stock or placed directly into the planting hole. Rose and Ketchum (2002a) found that fertilization of Douglas-fir seedlings resulted in increased growth only on sites having adequate soil water. The growth increases associated with fertilization were smaller and more transient than those from control of competing vegetation, probably because the latter is associated with increases in both soil water and nutrients. Roth and Newton (1996) reported decreases in Douglas-fir survival following fertilization with 200 lbs N/ac, a response they attributed, in part, to N-stimulated increases in the abundance of competing vegetation. Powers and Reynolds (1999) found that stem growth responses of ponderosa pine to competing vegetation control and repeated fertilization varied according to the inherent fertility and soil water availability of a given site, with greater responses to fertilization occurring on the less droughty sites.

Treatment Combinations

Various combinations of treatments have been tested during plantation establishment to determine whether they interact to produce synergistic, antagonistic, or simple additive responses of crop seedlings. Synergistic responses indicate that the combined effect of two or more treatments is greater than the sum of responses to the individual treatments applied alone. Antagonistic responses indicate that the combined effect is less than the sum of individual treatment responses, while additive responses occur when the combined effect is equal to the sum of the responses. For example, the addition of repeated fertilization to a sustained vegetation control regime caused neutral, additive, or synergistic responses of ponderosa pine growth, depending on whether the dominant factor limiting tree growth was soil water or fertility (Power and Reynolds 1999; R.F. Powers, personal communication). Rose and Ketchum (2002a, 2003) detected only additive responses of Douglas-fir growth to combinations of seedling size, fertilization, and area of vegetation control. Growth increases from fertilization were greatest on sites with adequate soil moisture, similar to the findings of Powers and Reynolds (1999), but these responses were short-lived as opposed to the sustained responses to vegetation control. Roth and Newton (1996) found that N fertilization had no effect on first-year survival and growth of Douglas-fir when the treatment was combined with control of competing vegetation, but in the absence of vegetation control it reduced seedling performance.

Alternative Crop Species

A wide range of factors are motivating forest managers to consider alternative crop species to Douglas-fir. Among many, these include development of new markets, declining availability of certain raw materials, and increased incidence of forest diseases. The widespread outbreak of Swiss needle cast has prompted increased interest in planting western hemlock on sites formerly planted with Douglas-fir. A survey of all major Westside forest landowners conducted by Briggs and Trobaugh (2001) showed the percentage of western hemlock planted either in mixture with Douglas-fir or by itself began a steady increase in 1999.

Previous research has shown how Douglas-fir, a species of moderate to low shade tolerance, tends to occur in the upper canopy while western hemlock, capable of living in lower light conditions, will occur in the lower canopy of natural stands (Oliver and Larson 1996, Lewis et al. 2000). The ability of these species to occupy different niches suggests that mixtures of them may be more productive than pure stands (Vandermeer 1989). Recent research assessing the differences between Douglas-fir and western hemlock growing in pure and mixed plantations has shown that only at high densities (700 trees/acre) will the cubic volume of mixed stands exceed that of pure stands of either species. Lower densities – 200 and 450 trees/ac – did not show productivity increases from the mixture (Amoroso et al. 2004).

Red alder has become a viable species for plantation silviculture on the Westside. Seed collection, nursery, and planting guidelines have been developed (Hibbs and Ager 1989, Ahrens et al. 1992). Recent interest has developed for planting hybrid poplar (hybrid of *Populus trichocarpa* Torr. & Gray and *P. deltoides* Bartr. ex Marsh.) on farmland in the Willamette Valley of Oregon because of its rapid growth and high yield on poorly drained clay soils (Hibbs et al. 2003). Such stands have produced up to 4000 ft^3/acre in six years on soils considered poor for agriculture.

Minimizing Browse Damage

Although a variety of barrier products exist for protecting conifer seedlings from deer and elk browse (Schaap and DeYoe 1986), many of these can restrict and deform shoot growth if not maintained properly. Gourley et al. (1990) compared growth of tall (2 ft) Douglas-fir seedlings following six methods of protection with or without control of competing vegetation. Control of competing vegetation had the dominant effect, increasing fifth-year height an average of 1 ft regardless of method of protection. In plots where vegetation was controlled, the methods of protection had neutral or negative effects relative to seedlings receiving no protection. It is likely that smaller seedlings, as well as those growing under intense competition, may benefit from protection because their smaller initial size may prolong the time period when they are susceptible to being browsed.

Protecting Soil Productivity

A better understanding of the effects of soil disturbance on forest productivity has been developed (Miller et al. 2004). For example, research in northern California has shown that soil compaction effects on seedling growth can be negative, neutral, or even positive depending on soil texture and soil water regime (Gomez et al. 2002). Reductions in Douglas-fir growth from soil compaction following ground-based harvesting have been shown to last as little as two years in coastal Washington and up to seven years in the Oregon Cascade Mountains (Heninger et al. 2002).

FUTURE NEEDS

Many of the advances in Westside silviculture have been the result of research aimed at providing greater understanding of the mechanisms of tree responses. In following with this approach, areas of research likely to advance the technology of Westside plantation establishment include:

(1) Species- and site-specific competition thresholds- How do tree responses to competing vegetation vary with species and site characteristics? Can models predicting these responses be used to refine vegetation management prescriptions and improve their cost-effectiveness?

(2) Seedling fertilization-What are the reasons for the limited responses of planted seedlings to fertilization, and what are methods that can be used to overcome these limitations?

(3) Minimizing animal damage-While considerable research has gone into developing various products and practices that protect seedlings from animal damage, very few have been shown to be cost-effective. Continued research and development is needed in this area to develop products or practices that reduce these growth losses.

(4) Silvicultural treatment interactions-Can treatment responses be predicted according to the limiting factors on a given site? A general model is needed that links seedling resource needs with the resource supplying power of the site and of specific silvicultural treatments.

(5) Predicting young stand development-New yield models and plantation site index equations are needed to forecast the differential growth rates resulting from various silvicultural treatments during plantation establishment.

(6) Plantation silviculture for alternative crop species- Advanced technology exists for establishing Douglas-fir plantations, yet basic information on seedling responses to treatment is still lacking for western hemlock, western red-cedar, and red alder. These information gaps must be filled if intensive management is to be applied to these alternative crop species.

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STATE-OF-THE-ART SILVICULTURAL TECHNOLOGY AND APPLICATIONS FOR FOREST STAND ESTABLISHMENT IN INTERIOR BRITISH COLUMBIA

John McClarnon[1] and R. Allan Powelson[2]

ABSTRACT

As part of the pressure to be competitive in international softwood markets, the British Columbia forest industries' post-harvest management objective has become the establishment of acceptable free growing stands at the lowest possible cost in the shortest timeframe. To achieve this objective, it is critical to understand, at a site-specific level, when and where to apply any given silviculture intervention and how effective it will be. As well, it is important to understand the costs versus benefits of different treatment options. Studies and operational experience in British Columbia, and especially in the sub-boreal spruce and black and white boreal spruce zones, indicate that the survival and early growth of conifer seedlings can be substantially improved through deployment of select seed, selection of appropriate species and stock type combinations, and through appropriate site preparation and brushing treatments.

KEYWORDS: Stand establishment, technology applications, limiting factors.

INTRODUCTION

In British Columbia, where approximately 95% of the forestland is publicly owned Provincial Forest, the government has the ultimate stewardship role and sets overall resource management objectives. Under an overarching legislative framework, harvesting rights and forest management responsibilities, including the mandatory achievement of government approved free growing stocking standards, are provided to the forest industry through an array of different agreements. In British Columbia, a "free growing stand" is defined as a stand of healthy trees of a commercially valuable species, the growth of which is not impeded by competition from plants, shrubs or other trees (BC Gov. 2004). The achievement of free-growing status is satisfied by attaining pre-determined standards for crop trees within a specified time period; height, height-above-competing brush, density, inter-tree spacing, and species composition (BCMOF 2000a).

Due to the intense pressure to remain competitive in international softwood markets, one of the overriding post-harvest stand management objectives for the British Columbia forest industry has become the establishment of acceptable free-growing stands at the lowest possible cost in the shortest timeframe. In this context, critical issues impacting even-aged stand establishment and management of lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) in the Sub-Boreal Spruce biogeoclimatic zone (SBS) and white spruce (Picea glauca [Moench] Voss) in the Boreal White and Black Spruce biogeoclimatic zone (BWBS) in interior British Columbia are reviewed.

PREDOMINANT LIMITING FACTORS

In the central and northern interior and higher elevations of British Columbia, combinations of any of the following limiting factors may be encountered; cold soil temperature, wet soils in spring, over-winter damage, severe frost events, very short growing seasons, late access to sites in the spring, deep snow packs and snow press (Meidinger and Pojar

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1991, Krasowski 1996). Damage from ungulates, hares, voles, cattle, porcupine, spruce leader weevil, pine stem rusts, and armillaria and tomentosus root diseases may be locally significant limiting factors (Meidinger and Pojar 1991). To provide examples of the application of silviculture technology in interior British Columbia, this paper focuses on sites within the SBS and BWBS zones where the predominant growth limiting factors are either cold soil temperature, spring soil saturation, summer drought conditions, a preponderance of vegetation competition from aspen (*Populus tremuloides* Michx.), hard pine stem rusts such as western gall rust (*Endocronartium harkenssii* (J.P. Moore) Y. Hirat) or a combination of any of these (Meidinger and Pojar 1991, McDowell 1998a, McDowell 1998b, Bedford et al. 2000, Bedford and Sutton 2000). In order to manage the impacts of these many limiting factors, forest practitioners in British Columbia have to use a variety of technologies and systems.

TECHNOLOGY APPLICATIONS

Biogeoclimatic Classification System

Successful site management begins with accurate identification and description of site characteristics. The Biogeoclimatic Ecosystem Classification (BEC) system, which integrates climate, soil and site features, and indicator plant species to group ecosystems (Meidinger and Pojar 1991), provides a "common language" to describe forest sites and is utilized by all forest practitioners throughout the province as the basis for silviculture prescriptions (http://www. for.gov.bc.ca/hre/becweb/). The classification system provides ecosystem specific recommendations for ecologically appropriate tree species rated on the basis of productivity, feasibility and reliability. Region specific field guides provide silviculture treatment recommendations, predictions of competing vegetation potential, and ecosystem specific recommendations for site preparation. Local hazards are communicated through ecological footnotes as microsite limitations (e.g., elevated microsites are preferred), mesosite limitations (e.g., restricted to southerly aspects), geographic restrictions (e.g., restricted to lower elevations of biogeoclimatic unit), pest limitations (e.g., risk of heavy browsing by moose), and abiotic limitations (e.g., risk of snow damage).

Improved Seed

Legislation has mandated that improved seed (that which has a genetic worth of five percent or greater and has desirable traits) must be used for reforestation when it is available and requires that all seed, either natural or improved, must be used in compliance with seed transfer guidelines. In British Columbia, the tree seed improvement program is a provincially co-ordinated co-operative venture between government and industry (FGC 2004). Program goals are to increase the average volume gain of select seed used for Crown land reforestation to 20% by the year 2020 and to increase select seed use to 75% of total provincial sowing by 2013 (FGC, 2004). In 2003, the deployment in British Columbia of seedlings grown from improved seed included planting 49 million interior spruce, 10 million lodgepole pine, 4.3 million western larch, and 1.1 million western white pine seedlings. Increasing genetic worth and the production of improved seed are leading to wider availability of faster growing seedlings.

Site Preparation

In the past, site preparation was applied extensively in interior British Columbia reaching a maximum of 101,009 ha in 1992/1993 (BCMOF 2000b). However, in recent years as the amount of area site prepared in interior British Columbia has dropped to 51,088 ha in 2002 (BCMOF 2003) (table 1), direct planting into appropriate micro-sites in undisturbed forest floor materials with minimal screefing has become a widespread practice (Heineman 1998). The suitability of this practice, however, depends on the sites limiting factors. For direct forest-floor planting to be a success in interior British Columbia, planting should occur: as soon after harvest as possible, on sites with adequate moisture throughout the growing season, on sites with reasonable soil temperatures, and only on sites that have low to moderate levels of competing vegetation unless viable options exist for vegetation management. (Heineman1998). Site preparation to reduce planting shock and improve survival and early seedling growth remains critical on sites with cold wet soils, very dry soils, growing season frost and/ or significant competing vegetation particularly where herbicides are not an option (Krasowski 1996, Sutton et al. 2001). Mechanical site preparation accounted for 75% of the 51,088 hectares treated in interior British Columbia in 2002. M o u n ding and disc trenching are the two most commonly employed site preparation methods. Other site preparation techniques include drag scarification to promote lodgepole pine natural regeneration, prescribed burning, and patch scarification.

In the SBS, direct forest-floor planting did not result in significantly lower lodgepole pine seedling survival (Bedford and Sutton 2000, Macadam et al. 2001). Similarly, white spruce exhibited the same general trends in the BWBS (Bedford et al. 2000) and the SBS (Sutton et al. 2001). While there may be little improvement in seedling survival with site preparation in the SBS and BWBS, there are significant early growth benefits (Krasowski, 1996, Bedford and Sutton 2000, Bedford et al. 2000, Byman 2000, Sutton

Table 1—Preparing sites for planting and natural regeneration on interior British Columbia Crown land in 2002/2003 (BCMOF 2003).

Treatment	Area in hectares
Biological	48
Burn	5,917
Chemical - air	0
Chemical - ground	232
Grass seeding	77
Manual	5978
Mechanical	38,836
Not specified	18
Total	51,088

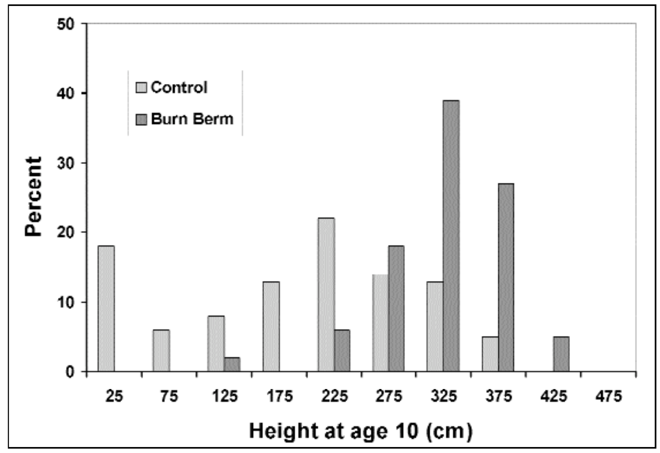

Figure 1—Height frequency distribution on unprepared vs. prepared sites.

Table 2—Effect of site preparation on time to free growing[a] condition and meeting green-up[b] requirements.

Treatment	Species	Years to free growing (2 m)		Years to green-up (3 m)
Untreated	Spruce	7		16
Herbicide	Spruce	6		11
Breaking plow	Spruce	5		10
		Well stocked	Minimum Stocking	
Untreated	Pine	7	11	9
Disc trench	Pine	6	7	8
Burn	Pine	5	7	7

[a] A free growing stand means a stand of healthy trees of a commercially valuable species, the growth of which is not impeded by competition.
[b] Stands are required to meet "green up", generally a height of 3 to 3.5 m of dominant trees of a commercial tree species, before adjacent stands or cutblocks can be harvested.

et al. 2001). These growth performance differences attributed to site preparation, however, diminished with time (Bedford and Sutton 2000, Bedford et al. 2000). Site preparation has also been shown to reduce the potential for over-winter injury resulting from freeze-desiccation (Krasowski 1996). Treatments that increased the root zone temperature of young seedlings reduced the potential for over-winter injury and damage (Krasowski 1996). As the root systems of established seedlings expand and exploit areas outside of the area of site preparation, growth of seedlings unimpeded by competing vegetation, is largely independent of micro-site and growth increments become uniform across treatment types (Bedford and Sutton 2000).

Another beneficial aspect of site preparation is the potential for uniformity of growth over the entirety of the growing site. Seedling establishment is more likely to occur on similar micro-sites after site preparation. This uniformity of micro-site selection results in greater uniformity of growth performance of seedlings across the growing site (fig. 1).

Uniformity of seedling performance across the growing site can result in earlier achievement of the seedling characteristics necessary for the statutory free growing obligations in British Columbia (table 2) (Bedford and Sutton 2000).

This improved growth performance, however, should not be expected to be maintained for extended time periods into the rotation of the stand.

Seedlings

Due to significant reductions in the use of herbicides, broadcast burning and mechanical site preparation, prompt planting of high quality seedlings has become the primary tool in addressing site-limiting factors. In British Columbia, approximately 85% of the harvested area is planted (BCMOF, 2003). Regeneration is primarily focused towards conifers with the exception of the boreal region where aspen and mixedwood stand regeneration is more common. Tree planting densities are usually in the range of 1200 to 1600 stems per hectare. Very low densities are prescribed in some fire prone natural disturbance ecosystems or where wildlife management objectives (e.g., continuous grizzly bear forage production) take precedence over timber objectives.

Development of container seedling techniques evolved in British Columbia in the 1970s. Continuous improvement since that time has resulted in large-scale production of high quality seedlings in a diversity of stocktypes (BCMOF 1998). Lodgepole pine and interior spruce account for 47% and 31%, respectively, of the approximately 234 million seedlings sown in British Columbia in 2004 (SPAR 2004). Greater than 90% of the sowing is to produce one-year-old container stock and the 410-styroblock container size (cavity volume of 80 ml) accounts for 40% (SPAR 2004) of the production. The majority of seedlings (80%) are planted in the spring window (to June 21st), with close to 20% as summer plant, and a small remainder as fall plant (SPAR 2004). While approximately 24% of the sowing (mostly lodgepole pine) is in copper treated container stock (SPAR 2004), little to no gain in survival and growth has been demonstrated from this treatment (Jones et al. 2002). The microsite that healthy seedlings are placed into is more important in affecting growth than the nursery treatment they were subjected to prior to planting (Jones et al. 2002).

Vegetation Management

Forest practitioners in the British Columbia interior may encounter any one of a multitude of vegetation complexes. These include the fireweed (BCMOF 1997c), fern (BCMOF 2002), ericaceous shrub and subalpine herb (BCMOF 1997b), pinegrass (BCMOF 1997e), reedgrass (BCMOF 2000c), dry alder (BCMOF 1997a), wet alder (BCMOF 1997f), aspen, and mixed broadleaf shrub complexes (BCMOF 1997e). A web-based stand establishment decision aid is now available to provide practitioners with access to the latest available information on vegetation management of different complexes. The key to minimizing and justifying expenditures is determining the appropriate situations, timing, and treatment types for vegetation management.

Approximately 60% of the 53,637 hectares brushed annually in interior British Columbia is done with manual techniques, including brush saws, chain saws, girdling tools, and manual stem snapping (table 3). Aerial spraying and ground based herbicide application account for approximately 25 and 15% of the brushing program respectively (BCMOF 2003). A widespread lack of public acceptance of the use of herbicides in British Columbia has limited the number of herbicides available, the situations where they can be used, and the methods of application that can be deployed.

Table 3—Brushing on interior British Columbia Crown land in 2002 and 2003 (BCMOF, 2003).

Treatment	Area in hectares
Biological	1,858
Chemical air	14,204
Chemical Ground	6,276
Manual – not specified	1,515
Manual – non-motorized	17,996
Manual – motorized	13,052
Mechanical	5
Not specified	191
Total	53,637

In the SBS and BWBS, aspen is one of the main competitors limiting coniferous growth potential. Strategies to reduce the impacts of aspen have been to leave it standing during harvest and girdle some of the residual stems so that approximately $5m^2$/ha remain to reduce sprouting, post-harvest foliar spray, cut-stump, and hack-and-squirt applications of glyphosate; basal bark and cut-stump applications of triclopyr; hand-snapping in mid-summer below the lowest live limb, cutting stems below the lowest live limb, and 2 entry manual brushings that retain sufficient aspen stems in the first entry to maintain conifer tree growth but reduce aspen coppicing.

Determining the amount of broadleaved basal area that can be retained without significantly reducing growth performance of the target crop species is essential in developing effective mixed-wood management stand establishment prescriptions and to determine acceptable levels of broadleaf components in free growing coniferous stands to maintain biodiversity and ecological functioning (Comeau et al. 1999, Comeau et al. 2003.). Species dependant factors such as leaf shape, size, orientation, and opaqueness impact light availability below broadleaf canopies (fig. 2) and light availability increases rapidly with height in a broadleaf canopy, even in dense stands where understory light availability is low (Comeau et al. 2003). Interest by forest managers in retaining either crop or non-crop broadleaved stems

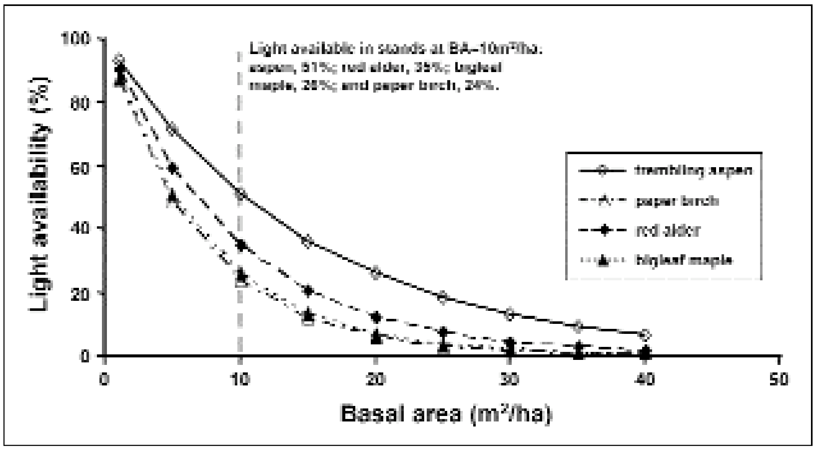

Figure 2—Light availability under broadleaf canopies.

in stands targeted for coniferous regeneration has led to the development of predictive models for aiding in the determination of the amount of broadleaf stems to be retained (Comeau et al. 2003).

Forest Health

Western gall rust is one of the significant growth limiting factors of lodgepole pine in both the SBS and BWBS zones (Fink et al. 1993, Reich 2002). Conducting forest health overview studies has identified fairly specific ecosystems where western gall rust will have a higher likelihood of impacting the regenerating stand (Reich 2002). Current management strategies for minimizing the impacts of hard pine stem rusts are the establishment and maintenance of high stand densities (Reich 2002). Stand establishment regimes being employed that can result in high densities on these sites include the encouragement of high natural regeneration levels (e.g. stump processing and chain-dragging), direct seeding (e.g., aerial, hand, or direct spot seeding), or high density planting (Reich 2002).

Costs

Cost of the technologies applied to achieve a free growing stand, as is legislatively required in British Columbia, varies widely (table 4). While individually some treatment costs may appear to be high, forest practitioners have to weigh this cost against the potential reductions in time to achieve the legislative growth obligations (table 2) that may be possible with the various combinations of these treatments. By fully understanding the growing site and its limitations, the goal of maximizing growth performance while minimizing total cost may be achievable.

Table 4—Range of current costs for silvicultural treatments in Interior British Columbia.

Treatment	Cost Range ($CAD/ha)
Broadcast burning	400 – 2000
Excavator mounding	700 – 900
Disk trench	180 – 220
Chain drag	180 – 250
Seed (B vs. A class)	16 – 84
Seedlings	186 – 545
Planting (no site prep.)	336 – 420
Planting (site prepared)	238 – 322
Direct seed/site prepared	400 – 550
Aerial herbicide spray	225 – 275
Backpack herbicide	300 – 700
Sheep grazing	260 – 400
Brush saw	450 – 500
Manually brush (1-m radii)	500 – 600
“Snap” aspen	250 – 350
Thinning	450 – 600
Pruning	550 – 900

Future directions

Future directions may include the development of approaches to assessing the free growing requirement that are linked to growth and yield objectives and assess achievement of the free growing objectives at a landscape level rather than at the individual cutblock level. Tools are required to predict appropriate mixtures of broadleaves and conifers for different crop objectives. Results in interior British Columbia remain variable with respect to seedling response following fertilization at time of planting or nutrient loading in the nursery and further work is required to improve consistency of response. Widespread loss of plantations to drought and fire in 2003 combined with large-scale forest health outbreaks (e.g., mountain pine beetle) suggests that climate change may become one of the most significant factors influencing future stand establishment.

SUMMARY

Studies and operational experience in British Columbia, including the SBS and BWBS zones, indicate that the survival and early growth of conifer seedlings can be substantially improved through deployment of select seed, selection of appropriate species and stock type combinations, and appropriate site preparation and brushing treatments. Choice of treatments that do not improve survival or growth or treatments that exacerbate the growth-limiting factors present on a site will fail to achieve the growth performance objectives in a timely manner and will lead to higher expenditures when trying to achieve the free growing obligations.

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STAND ESTABLISHMENT AND TENDING IN THE INLAND NORTHWEST

Russell T. Graham[1], Theresa B. Jain[1], Phil Cannon[2]

ABSTRACT

The moist, cold, and dry forests of the Inland Northwest occupy approximately 144 million acres. Ponderosa pine, lodgepole pine, western white pine, western larch, and Douglas-fir are usually the preferred commercial species of the area. These early-seral species are relatively resistant to endemic levels of insects and diseases. They tend to grow rapidly and in general produce commercial products at a young age, especially using focused management actions packaged in silvicultural systems that are documented in silvicultural prescriptions. Even-aged systems (clearcut, seed-tree, and shelterwood) are the most appropriate for growing commercial products. In limited circumstances uneven-aged systems may be appropriate on sites where ponderosa pine is the late seral-species. Planting of improved, site adapted trees usually offer the greatest control over the amount, kind, and establishment of plantations. The control of competing vegetation during the site preparation and tending phases of the silvicultural system is usually extremely beneficial in enhancing tree growth and product development. The forest soils of the Inland West are generally deficient in nitrogen and, in some settings, also potassium deficient. The organic and mineral surface layers, often containing ash and loess soils, are vulnerable to compaction, displacement, or damage from fires (prescribed and wild) or mechanical forest operations. Therefore, soil and its conservation should be integral to all activities included in a silvicultural system. For production forestry, herbicides offer an alternative that can maintain the soil resource yet control competing vegetation and most often yield excellent results when properly applied. Cleanings, weedings and thinnings are integral parts of the silvicultural system. These and all parts of silvicultural systems designed to produce commercial products can be readily quantified, displayed, and visualized (spatially explicit) through time using the Forest Vegetation Simulator.

KEYWORDS: Forest products, silvicultural systems, regeneration, stand tending, fertilization, site preparation, forest management.

FORESTS OF THE INLAND NORTHWEST

The Inland Northwest (144.2 million ac) forest region is defined by the Bitterroot, Selkirk, Cabinet, Salmon River, Lemhi, Steens, Purcell, Cascade, and Blue mountain ranges with many having elevations over 5,000 ft. This rough and complex topography results in a variety of forest settings ranging from steep slopes in narrow V-cut canyons to gentle rolling slopes in wide river valleys. During the Pleistocene, alpine glaciers shaped many of the canyons and valleys throughout the area. Now these glaciated landscapes are covered with a mantle of glacial till often compacted on the valley floors. Much of the fine silt outwashed by the glaciers was redeposited by winds leaving deep layers of loess deposits over many landscapes. Some 15,000 to 12,000 years ago, Glacial Lake Missoula repeatedly filled and emptied, flooding much of northern Idaho and eastern Washington removing topsoil and redistributing the surface sand, silt, and gravels. The eruption of pre-historic Mt. Mazama (Crater Lake, OR) about 7,000 years ago deposited a fine textured layer of ash up to 25 inches thick across the area. The granitic and metasedimentary rocks, ash, and

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loess deposits throughout the area are continually being modified by disturbance events giving rise to a wide variety of soils (Jain and Graham 2005, Quigley et al. 1996).

Moist marine air originating from the Pacific Ocean moderates temperatures within the Inland Northwest, while continental dry and cold air from the east brings cold weather in winter and hot weather in the summer. Dry Arctic air brings damaging frosts in winter and cool periods in summer and the interaction of the marine and continental masses brings convective precipitation and lightning in summer and warm wet periods in the winter. These air masses, along with the heterogeneous and rugged topography, create a highly variable climate, which in turn, supports mosaics of compositionally and structurally diverse forests. Historically (1850 to 1900), 19 percent (27.4 million acres) of the Inland Northwest (144.2 million acres) was covered by dry forests, with 30 percent of them occurring below 4,000 feet and the remainder occurring at higher elevations. Moist forests covered 18 percent (25.9 million acres) of the region. The cold forests historically made up 10 percent of the area with 99 percent of them growing at elevations exceeding 4,000 feet (Hann et al. 1997).

Moist Forests

Moist forests of the Inland Northwest occur in two locations, the eastern Cascade Mountains (east of the Cascade Crest in Washington and Oregon) and the Northern Rocky Mountains (northeastern Washington and Oregon, northern Idaho, and western Montana) (fig. 1). They grow at elevations ranging from 1,500 to 5,300 feet and occasionally occur at elevations up to 6,000 feet (Foiles et al. 1990, Graham 1990, Packee 1990, Schmidt and Shearer 1990, Hann et al. 1997) (fig. 1). These forests are influenced by a maritime climate with wet winters and dry summers. Most precipitation occurs during November through May, with amounts ranging from 20 to 90 inches (Foiles et al. 1990, Graham 1990, Packee 1990, Schmidt and Shearer 1990). Precipitation comes as snow and prolonged gentle rains, accompanied by cloudiness, fog, and high humidity. Rain-on-snow events are common January through March. A distinct warm and sunny drought period occurs in July and August with rainfall in some places averages less than one inch per month. Soils that maintain these forests include, but are not limited to, Spodosols, Inceptisols, and Alfisols. A defining characteristic of the Northern Rocky Mountains is the layer of fine-textured volcanic ash (up to 25 inches thick) that caps the residual soils.

For both locations, the vegetation complexes range from early- to late-seral, and occur within a landscape mosaic possessing all possible combinations of species and seral stages. Potential vegetation type (PVT) is a classification system based on the physical and biological environment characterized by the abundance and presence of vegetation in the absence of disturbance (Daubenmire and Daubenmire 1968, Hann et al. 1997, Smith and Arno 1999). They are defined by and named for indicator species that grow in similar environmental conditions (Hann et al. 1997). The PVTs in the Northern Rocky Mountains include western redcedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*) and grand fir (*Abies grandis*) with western white pine (*Pinus monticola*), western larch (*Larix occidentalis*), lodgepole pine (*Pinus contorta*), Douglas-fir (*Pseudotsuga menziesii*) and ponderosa pine (*Pinus ponderosa*) as the early- and mid-seral species (Daubenmire and Daubenmire 1968, Hann et al. 1997). The eastern Cascades PVTs include western redcedar, western hemlock, grand fir, white fir (*Abies concolor*), and noble fir (*Abies procera*). The early- and mid-seral species include lodgepole pine, Douglas-fir, and ponderosa pine while western white pine and western larch are less abundant when compared to forests in the Northern Rocky Mountains (Franklin and Dyrness 1973, Lillybridge et al. 1995).

Lush ground-level vegetation is the norm in the moist forests. The vegetation complexes are similar to those occurring on the west-side of the Cascade Mountains and in some Pacific coastal areas. Tall shrubs include vine maple, (*Acer circinatum)*, Rocky Mountain maple (*Acer glabrum*), Sitka alder (*Alnus sinuata*), devil's club (*Oplopanax horridum*), rose (*Rosa* spp.), gooseberry (*Ribes* spp.), huckleberry (*Vaccinium* spp.,) and willow (*Salix* spp.). Forbs include baneberry (*Actaea rubra*), pathfinder (*Adenocaulon bicolor*), wild ginger (*Asarum caudatum*), queencup beadlily (*Clintonia uniflora*), bunchberry dogwood (*Cornus canadensis*), and golden thread (*Coptis occidentalis*) (fig. 2).

Throughout the moist forests, native disturbances (snow, ice, insects, disease, and fire) singly, and in combination, created heterogeneity in patch sizes, forest structures, and compositions. Ice and snow created small gaps and openings, thinning forest densities and altering species composition. Native insects (e.g., pine beetle [*Dendroctonus* spp.]) and diseases (e.g., root rots [*Armillaria* spp.]), mistletoe (*Arceuthobium* spp.) infected and killed the very old or stressed individuals which tended to diversify vegetation communities (Hessburg et al. 1994, Atkins et al. 1999). Fires played a role in creating a mosaic of forest compositions and structures. Non-lethal fires (low intensity and severity surface fires that cleaned the forest floor, killed and/or consumed small trees and shrubs, and killed lower branches of overstory trees while leaving them alive) occurred at relatively frequent intervals (15 to 25 yrs) in a

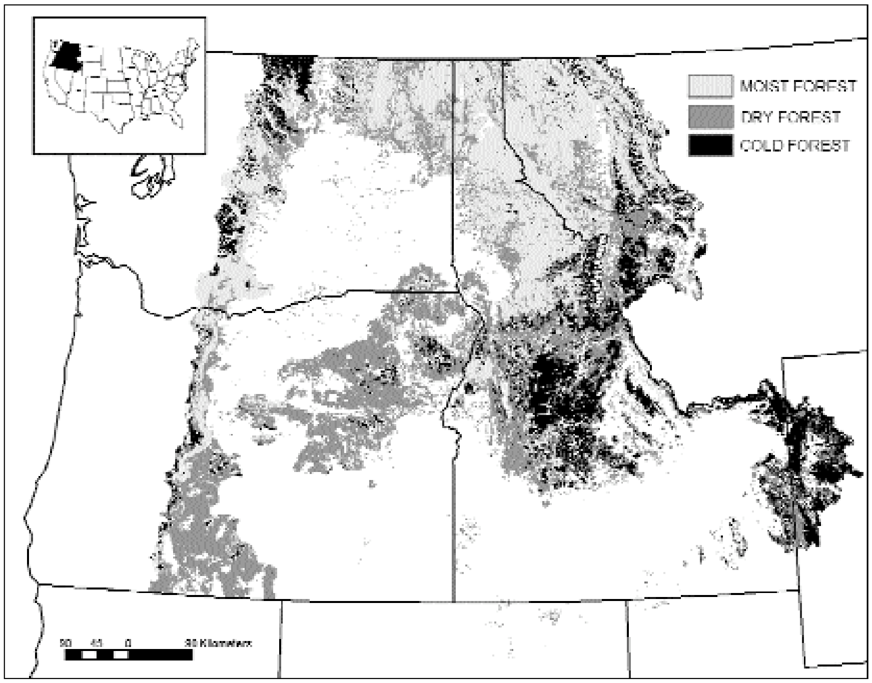

Figure 1—Extent of the forests of the Inland Northwest (144.2 million acres). The cold forests containing subalpine fir and Engelmann spruce potential vegetation types (PVTs) occupy 14.4 million acres (10%) of the area, the dry forests containing ponderosa pine, Douglas-fir, and dry grand fir PVTs occupy 27.4 million acres (19%), and the moist forests containing the moist grand fir/white fir, western redcedar, and western hemlock PVTs occupy 25.9 million acres (18%) (Hann et al. 1997).

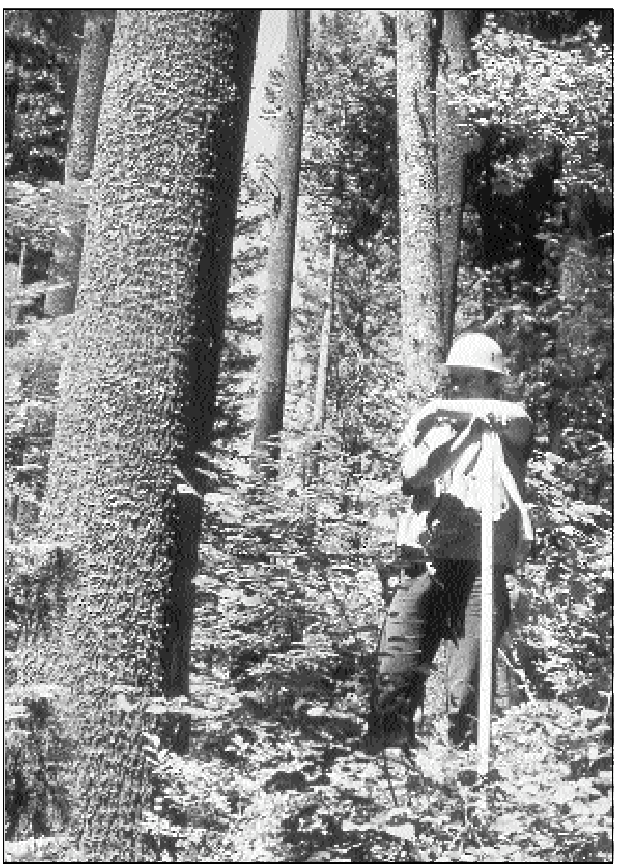

Figure 2—A young (100-year-old) stand of western white pine exhibiting a lush layer of ground-level vegetation located north of Wallace, Idaho.

quarter of the area. Lethal fires (intense and severe crown fires that killed and/or consumed the vegetation in all canopy layers) burned about a quarter of the area at intervals of 20 to 150 years but occasionally extended to 300 years. The mixed-fire regime (a combination of lethal and non-lethal fires) occurred across the rest of the moist forests at 20 to150 year intervals. Fires typically started burning in July and were usually out by early September when the weather changed (Hann et al. 1997). Although fire exclusion played a role in altering the moist forests of the Northern Rocky Mountains, introduction of a European stem rust, white pine blister rust (*Cronartium ribicola*) in 1910, caused the greatest change (Neuenschwander et al. 1999, Fins et al. 2001). The rust infects all five-needle pines, and subsequently decimated the abundant western white pine (fig. 3). Because the rust killed so many trees, the majority of surviving pines were harvested under the assumption they too would succumb to the rust (Ketcham et al. 1968).

Cold Forests

Within the Inland Northwest, cold forests occur at high elevations occupying about 10 percent of the area. They occur primarily in northern Idaho, central Idaho, and in the Northern Cascades Mountains of Washington (fig. 1). Growing seasons in cold forests are short, ranging from approximately 90 days at the lower elevations to just a few weeks at the higher elevations, and frosts can occur any time of the year. These forests are limited by poorly developed soils, and limited by moisture in some areas. Nearly

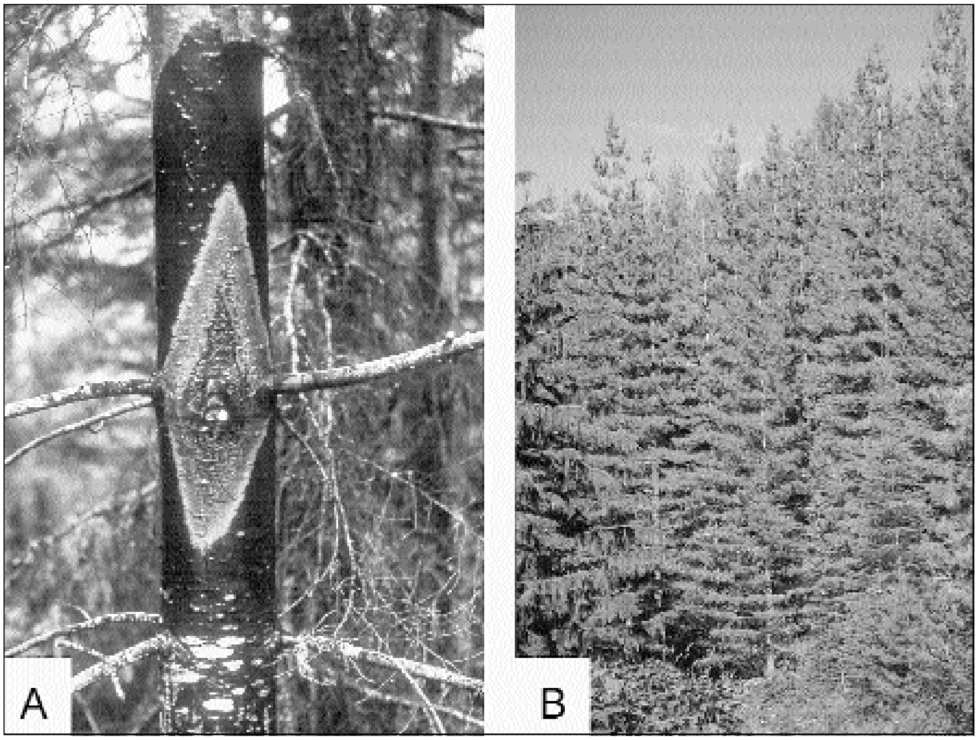

Figure 3—Western white pine blister rust (A), an introduced disease from Europe, in the early 1900s devastated much of the native western white pine. However through breeding programs and natural resistance, western white pine is once again a viable commercial species (B). This stand of first-generation blister rust-resistant pines is ≈ 50 years old, ≈100 to 120 feet tall, and ≈ 18 to 22 inches in diameter.

all (99 percent) of the cold forests occur over 4,000 feet, but cold air drainage allows some cold forests to extend below 4,000 feet (Hann et al. 1997).

On settings dominated by subalpine fir (*Abies lasiocarpa*), mean annual temperatures range from 25° to 40° F. Precipitation generally ranges between 24 and 75 inches with the majority falling in the form of snow and sleet. Snow comes early and stays late and can reach depths over 500 inches on settings in the Cascade Mountains with lesser amounts where lodgepole pine persists (central Oregon and central Idaho) (Alexander et al. 1990). The soils supporting the cold forest are relatively young. They were covered by extensive mountain glaciers during the Pleistocene and have been free of ice less than 12,000 years. At the higher elevations, most soil parent material is alluvium or glacial tills, but soil surfaces range from very weakly weathered (cobbly with no organic layers) to thick soils composed primarily of organic materials.

Like the moist forests, lush ground-level vegrtation is the norm for most settings in the cold forests. Tall shrubs include false huckberry (*Menziesia ferruginea*) and Sitka alder while the dominant medium and low shrubs are often huckleberries. Pinegrass (*Calamagrostis rubescens*), bluejoint reedgrass (*Calamagrostis canadensis*), and elk sedge (*Carex geyeri*) typify the graminoids occurring in the cold forests. Some of the most commonly occuring forbs include beargrass (*Xerophyllum tenax*), round-leaved violet (*Viola orbiculata*), and queencup beadlily (Cooper et al. 1991).

The PVTs dominating the cold forests include subalpine fir and subalpine fir/Engelmann spruce (*Picea Engelmannii*). Western larch and lodgepole pine are early-seral species in the subalpine fir/Engelmann spruce PVT, Douglas-fir and western white pine are mid-seral species, and grand fir, Engelmann spruce, and subalpine fir are late-seral species (fig. 4). The mixes of these species occurring in the subalpine fir/Engelmann PVT are highly dependent on elevation (and associated climate), and disturbance frequency and type.

Depending on the physical setting, the cold forests of the Inland Northwest historically (1850-1900) burned at 25 to 100 year intervals. Approximately 10 percent of these forests were burned by non-lethal surface fires, every 30 to 100 years. Lethal crown fires burned 25 to 30 percent of the cold forests every 30 to 100 years with the longer intervals occurring in moist areas. During the short fire season (≈ 60 days), a mixed fire regime burned about 60 percent of the cold forests at 25- to 100-year intervals, with occasional large fires occurring every 100 years (Hann et al. 1997).

Figure 4—A thinned stand of lodgepole pine (an early-seral species) growing on a subalpine-fir potential vegetation type.

Figure 5—A young (70-year-old) ponderosa pine stand being maintained by a low intensity surface fire. Note the presence of some ground-level vegetation.

Dry Forests

Dry forests occur across a wide range of elevations in northeastern Washington, northeastern Oregon, central and southern Idaho, and south-central Oregon (fig. 1) (Hann et al. 1997). Soil parent materials include granites, metasedimentaries, glacial tills, and basalts. Vegetation in these forests is usually limited by water availability and often is subject to drought. Nutrient deficiencies develop in eroded areas that can limit forest development. Douglas-fir, ponderosa pine, and dry grand fir/white fir (PVTs) dominate these settings (Hann et al. 1997). When western larch is present in dry forests it is always an early-successional species (dominant after disturbance). Grand fir/white fir or Douglas-fir are late-successional species that are usually more shade-tolerant than the early-seral species they succeed, while ponderosa pine can play both roles, depending on the PVT (Daubenmire and Daubenmire 1968, Hann et al. 1997). Surface vegetation in the dry forests includes shrubs (kinnikinnick (*Arctostaphylos uva-ursi*), *Ceanothus* spp., snowberry (*Symphoricarpos albus*), ninebark [*Physocarpus malvaceus*]), grasses (pine grass) e.g., bromes (*Bromus* spp.), and sedges (*Carex* spp.) (Foiles et al. 1990, Hermann and Lavender 1990, Oliver and Ryker 1990) (fig. 5).

Fire, insects, diseases, snow, ice, and competition thinned these forests, and surface fires provided opportunities for plant regeneration (Pearson 1950, Foiles et al. 1990, Hermann and Lavender 1990, Oliver and Ryker 1990). In concert, these disturbances historically maintained a variety of structural and successional stages. Fire exclusion, harvesting, and changes in fire regime altered the composition and structure of the dry forests (Hann et al. 1997). The area burned currently by non-lethal surface fires is estimated to be less than 50 percent of the dry forests and the mean interval of these fires is estimated to be to 40 to 80 years. Mixed-fires are estimated to burn 35 percent of the dry forests with a mean interval of 45 to 60 years and lethal fires are estimated to burn 20 percent of the dry forests at mean intervals of 45 to 60 years (Hann et al. 1997).

FOREST SOIL

Soil is the foundation of a forest ecosystem and its character is a major contributor to site productivity (Harvey et al. 1987). In general, nitrogen (N) is the most limiting nutrient in most forests (Moore 1988, Moore et al. 1991). However, there is evidence that potassium (K) also plays a key role, especially in relation to disease and insect infestation (Moore et al. 1994). As stated earlier, much of the Inland Northwest is covered by rich loess and ash soils.

These materials, along with the weathering of the parent materials (granitics, basalts, meta-sediments), all contributed to the productivity of the forest. Therefore, conservation of the soil resource is essential to maintain and sustain forest productivity.

The character of the litter, humus, soil wood, and surface mineral layers of forest soils are critical when developing silvicultural systems (Harvey et al. 1987, Jurgensen et al. 1997). These soil layers are most easily and commonly disturbed by silvicultural activities, yet they are crucial to forest productivity. Depending upon the setting, organic matter (OM) is generally concentrated near the soil surface. Organic matter maintains the nitrogen cycle in soils through its decomposition and by facilitating N fixation (the process of making elemental N into a form that plants can use) and N storage of N (Jurgensen et al. 1979). Physical properties and nutrition are very important soil attributes but the biological component is integral for maintaining forest productivity. In particular, ectomycorrhizae (fungi that have a symbiotic relationship with the plants) and their environment are critical for maintaining soil productivity. Ectomycorrhizae establish on the root systems of trees and facilitate the uptake of both water and nutrients by the tree, which in turn supplies nutrients to the fungi (Harvey et al. 1981, Harvey et al. 1987).

Woody Residues

Although they are not a soil component, the quantity, quality, and disposition of coarse woody debris (CWD) can influence forest soils (Harvey et al. 1987, Jurgensen et al. 1997). The quantity of downed material can vary dramatically, depending on site, forest conditions, and forest treatments (Brown and See 1981). Physically, woody residues protect soil from erosion, displacement and compaction. Residues provide shade and protection from wind and snow and can protect newly established seedlings from livestock (Edgren and Stein 1974, Graham et al. 1992). However, falling or rolling logs can damage regeneration and fuel loadings can threaten forests by increasing the fire hazard (Brown et al. 2003). Decaying logs, especially those with the incipient and advanced forms of decay, are excellent substrates for non-symbiotic nitrogen fixation and if nitrogen-fixing plants such as ceanothus (*Ceanothus* spp.), buffaloberry (*Shepherdia canadensis*), or leguminous forbs are not present, non-symbiotic forms of nitrogen fixation can be significant.

In addition to CWD, organic input to forest soils comes from many other sources. Grasses, shrubs, root turnover, needle fall, etc. contribute to soil OM. In general, CWD

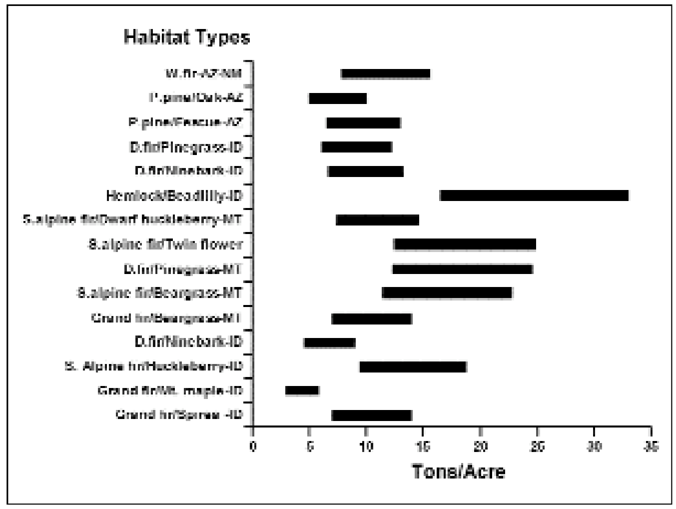

Figure 6—The amount of coarse woody debris suggested by Graham et al. (1994) for maintaining soil productivity in the forests of the Rocky Mountains. A=Arizona, I=Idaho, M=Montana for the habitat types where the recommendations apply.

comes from tree boles and limbs over three inches in diameter (smaller material is usually considered a fire hazard). Accumulation of CWD on the forest floor depends upon the amount of decomposition occurring on a site and the frequency and severity of wildfires that burn a forest (Brown and See 1981, Brown 1983). In general, those forests that were frequently burned by low intensity surface fires tended to accumulate and use less CWD than the cold and moist forests with long fire-return intervals (Graham et al. 1994a, Hann et al. 1997). The amount of CWD suggested for maintaining soil productivity ranges from 3 tons per acre on ponderosa pine settings to over 30 tons per acre on western hemlock settings in moist forests (fig. 6) (Graham et al. 1994a).

Litter

Unconsolidated and undecomposed litter directly provide both N and ectomycorrhizae habitat for soil function. This material is composed of organic materials from trees, shrubs, grasses, forbs, and other plant material. Litter is not usually important for ectomycorrhizal activity, but if moisture is maintained in these layers, ectomycorrhizae can be present (Harvey et al. 1987). However, through its decay, litter becomes a greater soil contributor. Litter can vary widely in amount, composition, and structure depending on forest type and PVT, as well as fire-return interval and decomposition rate. Litter protects the soil from erosion and retains moisture in the lower layers (Pannkuk and Robichaud 2003.) and protects soils from compaction (Lull 1959). Litter can be an impediment to both natural and artificial tree regeneration. If the litter layer is thick, which often

Figure 7—A large accumulation of brown cubical rotten wood occurring in a lodgepole pine stand near Butte, Montana. In these forests, this material can be a major component of the surface soil.

occurs in ponderosa pine forests where decomposition is slow and fire has been excluded, tree seeds falling on this layer germinate, but root elongation may not keep pace with litter drying (Haig et al. 1941, Pearson 1950). On the other hand, if litter remains moist during germination and early seedling growth (a situation that may be found in many moist forests), establishment of tree seedlings on organic layers is quite common (Minore 1972). Because this most often occurs in the moist and cold forests with late seral species, the desired mix of species for commodity production is not often realized.

Humus

Even though the humus (decomposed material in which plant parts are indistinguishable) soil layer may be very thin (i.e. < 0.25 in), it can be a prime site for both N and ectomycorrhizae. For example, in the surface 12 inches of a Douglas-fir/ponderosa pine forest soil, over 20 percent of the total N can occur in the humus and over 30 percent of the ectomycorrhizae (Harvey et al. 1987). In addition, it often has high moisture contents and is rich in calcium, potassium, and magnesium. This layer often represents the transition between organic layers and the mineral soil and, when it is burned over, it is a superb site for seed germination and seedling establishment (Haig et al. 1941).

Soil Wood

A component of forest soils that is often over looked is soil wood which is highly decomposed wood incorporated into mineral soil horizons and is usually in the form of brown cubicle rot (fig. 7) (Harvey et al. 1987). As it ages and further decomposes, it can take on a much finer texture. As with the other organic components of soil, the quantity and character of soil wood can be quite variable. For example, the amount of soil wood in the surface 12 inches of a forest soil is 20 percent in cold forests, 22 percent in Douglas-fir forests, and over 26 percent in moist forests (Harvey et al. 1987). Soil wood does not usually occur as a layer within soil but rather occurs in deep pockets created by buried logs and decaying stumps (Reinhardt et al. 1991). Soil wood protects soils from compaction, provides OM to the mineral soil, is also an important source of N (≈20 percent of the amount in surface 12 inches of soil) and is an excellent substrate for ectomycorrhizae (≈50 percent of the amount in surface 12 inches of soil) (Harvey and others 1987). Because of its water-holding availability and nutritional, biological, and physical characteristics, soil wood is often prime habitat for rooting. In the cold forests, these materials, intermingled with exposed parent material, can constitute the majority of the soil (Graham et al. 1994a). Forests dominated by pines and Douglas-fir develop brown cubical rotten wood products that are deposited on the forest floor and are subsequently incorporated into the mineral soil. These products can persist in soils for hundreds of years and during that time provide soil structural and nutritional benefits. In contrast, grand fir/white fir develop white rotten wood products that are dispersed in soil relatively rapidly (decades), thus shortening their contribution to soil productivity (Larsen et al. 1980, Harvey et al. 1987).

Surface Mineral Soil

The surface 6 to 12 inches of mineral soil is derived from the deposits and parent materials of the site, but is also highly influenced by vegetation, surface organic layers and disturbance history inherent to the PVT. The OM incorporated into shallow mineral horizons carries important properties into the mineral soil. Mineral soil with robust OM amounts has better nutrition, water-holding capacity, and structure than soils with small amounts of OM. In addition, OM-rich mineral soils are excellent sites for nitrogen fixation and ectomycorrhizae (Harvey et al. 1987). Surface mineral layers are highly susceptible to compaction and displacement and soils with high volcanic ash content are particularly sensitive to forest operations (Harvey et al. 1989b).

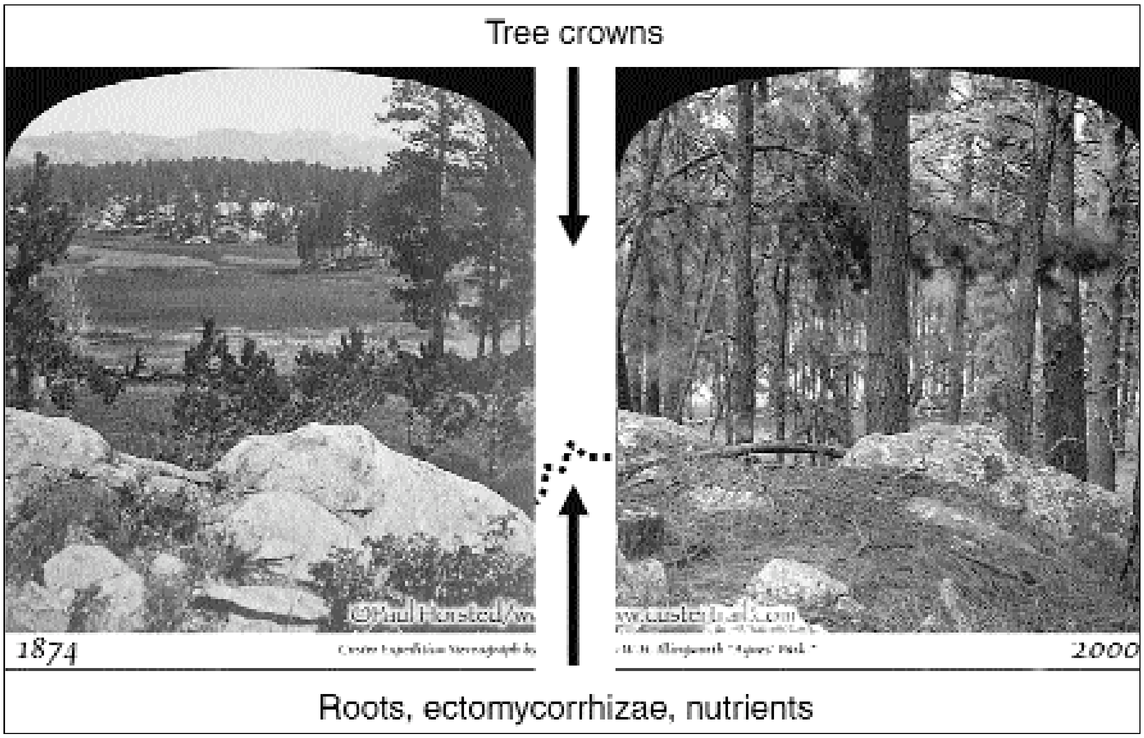

Figure 8—When fires are excluded from ponderosa pine forests, organic layers tend to accumulate and tree roots, ectomycorrhizae, and nutrients tend to concentrate in these layers. Note the contrast between the amount of organic material on the forest floor when General Custer came through the Black Hills in 1874 and the amount that has accumulated around the rocks by 2000. Photos courtesy of Paul Horsted/custertrail.com (Grafe and Horsted 2002).

Altered Forest Soils

Soils in many forests are different from those that occurred historically. Soils have been altered through species changes (within shrub, tree, or forb components), organic material accumulation on the forest floor, and by soil compaction and displacement. These changes have been the result singly, or in combination of fire exclusion, timber harvesting, animal grazing, and climate shifts. There is a gradual shift in the proportion of soil nitrogen reserves and OM in mineral layers of pine forests to surface organic layers in fir forests. Accumulation of both above-and below-ground biomass from roots, needles, and boles in fir forests is accelerating activities of decomposers by increasing and changing the basic substrate they utilize (Harvey 1994). Associated with these changes in litter type and quantity is a likely change in soil surface chemistry, including allelopathic substances with the potential to alter a variety of microbial activities (Rose et al. 1983). Forests dominated by grand fir tend to concentrate both nitrogen and potassium in their foliage; these forests often have live crowns extend down to the soil surface (Mika and Moore 1990, Moore et al. 1991). In general, this combination of a low canopy structure with nutrients and microbial activities concentrated in or near the soil surface make both of these critical ecological resources susceptible to mechanical and fire destruction (fig. 8).

GROUND-LEVEL VEGETATION

In the forests of the Inland Northwest, ground-level vegetation is highly diverse with the cold and moist forests containing lush and diverse shrub, grass, and forb communities (fig. 2) (Daubenmire and Daubenmire 1968, Pfister et al. 1977, Cooper et al. 1991). Each plant in these communities has a different strategy for reproducing and surviving disturbances (Noste and Bushey 1987). Ground-level vegetation can also play many roles such as maintaining nutrients on a site after a disturbance, providing OM to the forest floor, protecting soils from erosion, and facilitating nutrient cycling (Yarie 1980, Pannkuk and Robichaud 2003). These plants tend to turnover a greater percentage of their biomass each year through litter fall than do trees. Therefore, they tend to cycle nutrients and OM more readily than trees.

Ground-level vegetation often aggressively responds to canopy openings and forest floor disturbances. Species that may not be present before a disturbance can proliferate after a disturbance. For example, canopy removal and prescribed fire can facilitate robust development of *Ceanothus* spp. especially in the cold and moist forests even though none was present pre-disturbance. Seeds of *Ceanothus* spp. lie in wait in the forest floor for scarification through heat to germinate; these species can rapidly occupy a site after disturbance (Noste and Bushey 1987). Other ground-level vegetation, such as alder, willow, and maple, are aggressive resprouters from the root crown, rhizome or above-ground stem. Some species are exceptional at resisting or enduring disturbances. For example, pine grass in the dry and moist forests and bear grass in the cold forest readily survive disturbances.

When it comes to producing forest crops, ground-level vegetation often competes aggressively with the establishment and growth of conifers (Baumgartner et al. 1986, Boyd 1982). In all forests, the forb, shrub, and grass layers can present formidable competition for nutrients, water, and light with tree seedlings. In addition, it can interfere with conifer development by occupying sites with roots, even though the area appears to be unoccupied and, even though ground-level vegetation may be dead, its root systems can interfere with tree planting. Also, ground-level vegetation can be allelopathic, that is emitting toxins both when the plant is alive and dead, interfering with seed germination and tree development (Ferguson 1991). Indirectly, ground-level vegetation can supply habitat for damaging animals, facilitating trampling, browsing and girdling damage on plantations (Kingery and Graham 1991, Graham et al. 1992, Ferguson 1999).

SILVICULTURAL SYSTEMS

In general, silviculture can be defined as the art and science of controlling the establishment, growth, competition, health, and quality of forests and woodlands to meet the diverse needs and values of landowners and society on a sustainable basis (Helms 1998). The processes silviculturists use to manipulate forest vegetation are included in a silvicultural system and documented in a silvicultural prescription. A silvicultural system outlines a series of treatments over the life of a stand to fulfill a set of values or interests for a particular landowner (Schlich 1906). The prescription is the formulation of a silvicultural strategy using biological, managerial, and economic knowledge to meet stand management objectives (Smith et al. 1997, Nyland 2002). This plan should ensure that future yields of goods are conserved while harvesting or utilizing currently available goods (Smith et al. 1997). Most often, the early- and mid-seral species are the fastest growing and most tolerant of endemic diseases and insects and are readily managed using well-honed silvicultural systems so, therefore, they are the preferred species for timber and fiber production.

Even-Aged Silvicultural Systems

Even-aged silvicultural systems usually create and maintain stands with trees representing one age class, or a narrow range of age classes. Historically, lethal fires created forests containing even-aged stands. In general, clearcut, shelterwood, and seed-tree systems can emulate these stand-replacing events but these tend to perpetuate early-seral or relatively intolerant (e.g., shade, canopy closure, competition) trees.

With the exception of the clearcut, the other even-aged silvicultural systems (seed-tree and shelterwood systems) include some high forest cover during a portion of the system development. Overstory density and the species prescribed in seed-tree and shelterwood systems depend on the site and desired forest structure and composition. The number of overstory trees prescribed in a shelterwood depends on how much shelter is required to successfully regenerate a desired tree species. As canopy cover increases, the amount of shade-tolerant (e.g., grand fir, hemlock) regeneration will also increase.

Clearcut Method

The clearcut regeneration method is easy to apply and is often well suited for situations where disease and/or insect problems exist. Disposal of hazard fuels and site preparation can readily be accomplished using prescribed fire, mechanical means, or chemical application. In addition, the planting of improved stock from tree improvement programs is facilitated by the clearcut method. Clearcutting is most applicable on sites and PVTs in which biophysical conditions present without canopy cover provide suitable conditions for seedling establishment and development (e.g., western hemlock and subalpine fir PVTs, northerly slopes etc.) (fig. 9). The optimum size and orientation of the clearcut is also predicated on the biophysical setting and the species and kind of regeneration desired (Burns 1983). If natural regeneration is planned, then ample seed and dispersal will need to be available from neighboring seed walls (clearcut edge) or within the tops of the trees left after harvesting.

Figure 9—A clearcut regenerated with western white pine located near Coeur d'Alene, Idaho. Note the well-defined seed wall (clearcut edge).

Seed-Tree Method

The seed-tree method can be applied on all slopes and aspects but needs to be tailored to the forest PVT and biophysical setting. Vigorous, wind-firm trees should be left as seed trees and selected for their phenotypic traits (Hoff et al. 1976). On most settings, four to six trees per acre are adequate for seed production for most preferred species. For example, 7 to 12 trees/acre might be prescribed for a poor seed-producing species (western larch), whereas 3 to 7 seed trees/acre might be utilized with a prolific seed-producing species (western white pine). If possible, site preparation should coincide with a seed crop in the overstory. The seed trees should be removed as soon as possible after regenerationbecomes established. Stocking control is usually needed to maintain the desired number and species composition in the regenerated stand (Schmidt 1988). The seed-tree method is ideal where seed dispersal could be problematic from adjacent seed walls if the clearcut method was applied. This often occurs with ponderosa pine because it has heavy seeds that are dispersed shorter distances compared to some of the mid- and late-seral species such as grand fir and Douglas-fir (Haig et al. 1941, Burns 1983) whose seeds disperse longer distances.

Shelterwood Method

The shelterwood regeneration method is applicable on all aspects and slopes, but is especially suited to steep, dry slopes where regeneration would benefit from protection. Dominant overstory densities used in this method range from 15 to 40 trees per acre depending on species. The greater the number of trees left in the overstory, the greater the proportion and number of shade-tolerant species regenerated (Haig et al. 1941). Because of the wide range in fire resistance of the species occurring on these sites, slash disposal and site preparation may be difficult and expensive depending on species and slope. Vigorous trees should be left in the overstory to withstand the shock of release, stand through weather events (e.g., snow, wind) and act as good seed producers. When an adequate regeneration is achieved, the overstory should be promptly removed (Burns 1983).

Application of Even-Aged Systems

In the cold forests, the clearcut and seed-tree methods are very appropriate for producing even-aged stands of early-seral species (e.g., western larch, Douglas-fir). Lodgepole pine is the most frequently managed species within the cold forests because it readily germinates and develops using clearcuts on the subalpine fir PVTs (Schmidt and Alexander 1985) (fig. 4). Serotiny in lodgepole pine usually ensures the presence of viable seed in the unopened cones present in the slash left after harvesting. However, diligence is needed when disposing of slash and preparing sites to insure the seed stored in the cones is not removed or destroyed. Cone serotiny is variable in lodgepole pine; therefore the presence of unopened cones should be verified prior to relying on this characteristic to supply seed for regeneration (Lotan 1973).

Western larch is often a preferred early-seral species in the cold forests and it also regenerates and develops well using the clearcut system (Schmidt and Shearer 1990). Douglas-fir is more intermediate in response to clearcutting in these

Figure 10—A shelterwood system was used to regenerate western white pine. Rust-free shelter trees were chosen. The seedlings regenerated using this method could exhibit up to 19% resistance to blister rust (Hoff et al. 1976).

settings but it also responds better to the open conditions of a clearcut than spruce and subalpine fir, species that are late-seral associates in these cold forests. In portions of the dry forests, especially those on the more moist PVTs such as the drier grand fir/white fir settings, clearcutting has been successfully used to perpetuate ponderosa pine (Ryker and Losensky 1983).

Clearcutting is very applicable for use in the moist forests (fig. 9). The preferred early-seral species, western white pine, western larch, and Douglas-fir, all regenerate and develop readily using this method. In addition, because of the large amounts of fuel that can be created when harvesting, clearcuts facilitate the use of prescribed fire for preparing sites for both natural and planted regeneration which will decrease the wildfire hazard (Haig et al. 1941, Graham et al. 1983). Regeneration of late-seral western hemlock, grand fir, and western redcedar is often prolific in the moist forests; however, clearcuts tend to favor the early-seral species over the late-seral species, particularly if the preferred species regenerate promptly after harvest (Haig et al. 1941, Graham et al. 1983, Jain et al. 2004). Moreover, some suggest that clearcuts are the preferred method for managing rust-resistant western white pine (Fins et al. 2001).

Seed-tree methods are most applicable in the cold and moist forests but also have been used successfully in the dry forests on settings in which shelter is not a prerequisite for successful regeneration (Ryker and Losensky 1983). Very often this occurs on PVTs where ponderosa pine readily regenerates such as those occurring in the Black Hills and some sites in Arizona and New Mexico (Pearson 1950, Shepperd and Battaglia 2002). Seed-tree methods can be used in the moist forests to regenerate western white pine, Douglas-fir, and western larch (Haig et al. 1941). In the cold forests, the seed-tree method can be used to regenerate western larch and Douglas-fir and is very applicable in situations where lodgepole pine does not express cone serotiny (Lotan 1973).

Shelterwood regeneration methods are most applicable on settings in which the preferred species, usually an early-seral species, benefits from the presence of shade. This can occur on Douglas-fir and ponderosa pine PVTs in the dry forests where ponderosa pine regeneration benefits from some shade (Pearson 1950, Ryker and Losensky 1983, Shepperd and Battaglia 2002) (fig. 5). In the moist forests, western white pine readily regenerates with the shelterwood method and, in many settings, it prefers partial shade for the first few years of its life (Haig et al. 1941) (fig. 10). Ponderosa pine is often regenerated using one or two stage shelterwoods (Pearson 1950). The preparatory cut favors seed producing pine developing their wind firmness and crown expansion, and the final seed cut provides growing space for the seedlings to be established (Boldt and Van Deusen 1974). By providing these openings, ponderosa pine has the greatest opportunity to become established and outcompete its late- and mid-seral associates such as Douglas-fir, grand fir, and white fir (fig. 5). However, in many settings Douglas-fir would also be the preferred species especially on the drier grand fir or white fir PVTs.

A consistent drawback of using seed-tree and shelterwood regeneration methods is the possibility of perpetuating dwarf mistletoe (*Arceuthobium* spp.). Ponderosa pine, Douglas-fir, western larch, and lodgepole pine, depending on the location and PVT, are all susceptible to infection from mistletoe. Trees without mistletoe can be selected for retention but if the disease is prevalent in the overstory, the clearcut method usually provides more satisfactory control of the disease (van der Kamp and Hawksworth 1985).

Trees in shelterwood and seed-tree systems can be grouped or spaced based on species composition or other designated criteria. The seed-tree and shelterwood component used in these systems can be short- (removed early in the life of the regenerated stand, 30 yr or less) or long-lived (left on the site through the life of the regenerated stand). However, for use in most production situations, prompt removal of seed and shelter trees, once regeneration is established, is preferred. The longer the overstory remains, the more likely tolerant species will develop and compete with the preferred intolerant species.

Uneven-Aged systems

From a timber management perspective, uneven-aged systems are most likely applicable only on limited sites in which a frequent and continual flow of wood products would be desirable. Uneven-aged systems, both in groups and individual trees, have been used successfully in the ponderosa pine PVTs (Shepperd and Battaglia 2002). However, because these systems perpetuate late-seral species or those favored with closed canopy conditions, uneven-aged systems in most situations would not be preferred for production forestry. However, uneven-aged systems do not have applicability on small scales such as for non-industrial private landowners (Graham and Smith 1983, Graham et al. 1999a)

SITE PREPARATION

The most important component of site preparation is to prepare sites to meet sound and well thought-out objectives. A prescription provides the plan on the kind, composition, and amount of regeneration desired. This plan includes describing seedbed and/or planting site requirements along with the amount, and species (kind) of competing vegetation inherent to the site and its expected response to fire, mechanical, or chemical disturbance. Potential vegetation, habitat types or similar vegetation classifications usually offer excellent descriptions of ground-level vegetation and the seral stage of forest development it in which it commonly occurs (Daubenmire and Daubenmire 1968, Pfister et al.1977, Cooper et al. 1991). In addition, these classifications provide insight into species that may be absent preharvest and their expected response to disturbance.

Figure 11—A helicopter igniting a prescribed fire in a clearcut near Sandpoint Idaho. The fire was ignited in the evening ensuring that moisture contents in the lower duff were above 100% and the fine fuel moisture contents were conducive for producing a low severity fire.

Ideally, silvicultural systems should be designed to minimize competing vegetation without using expensive control measures. However, disposal of the slash left after yarding also affects soil compaction and soil organic content (Harvey et al. 1987, Page-Dumroese et al. 1997). Broadcast burning is commonly used to prepare sites throughout the Inland Northwest but slash is also burned after machine piling (fig. 11). Whatever method is used, the objectives of site preparation commonly include reducing fire hazard, providing planting access, and controlling competing vegetation (Baumgartner 1982 Lotan 1986).

In cold, dry, and moist forests, the amount of moisture available to young trees during the summer months is almost always the single most important determinant of whether a planted seedling will survive and the rate at which this seedling will grow (Cleary and Greaves 1976). Of course not all water in a soil profile will be available to regenerated trees. Some will percolate out of the soil profile, some will evaporate, and much will be used by competing vegetation. Effective site preparation can dramatically increase plantation survival and development. Powers and Reynolds (1999), for example, showed that by completely removing competing vegetation, ponderosa pine volume growth was 400 percent greater 10 years later when compared to tree growth on areas with competing vegetation.

Figure 12—A Salmon blade can be used to effectively prepare sites subject to pine grass competition yet still conserve the nutrient-rich surface soil layers.

Mechanical Preparation

Depending on soils and steepness of slope, timely and proper site preparation most often can be accomplished by using machinery. This usually assures excellent site preparation even with sprouting and herbicide resistant species. For example, *Ceanothus* spp. is often effectively controlled mechanically since this method does not heat scarify seeds stored in the forest floor. Depending on equipment and soil conditions, most machines (except cable machines) can safely and effectively operate on slopes with gradients less than 30 to 40 percent (Miller 1986a). Machine methods include rakes pulled or pushed by tractors, special dozer blades, and cable scarifiers to name a few (Lowman 1986). Very often the site preparation is accomplished simultaneously with reducing the wildfire hazard. In general, machines capable of separating slash of different sizes, often called "grapple machines", displace less soil than rakes attached to the front of tractors; thus the use of grapple machines can help conserve and protect soil layers (Graham et al. 1994a).

Competition from pine grass and other sod-forming grasses present different germination and planting problems than shrub competition. A mechanical option that has shown success for both planting and seed germination is a tractor-mounted rake that exposes mineral soil and prepares planting sites yet does not displace the soil. The machine uses a plow shear blade that rolls the sod, exposes the grass roots, and decreases its survivability, and exposes mineral soil (MTDC 1988) (fig. 12).

In contrast to machinery in the form of tractors, excavators, and other machines, hand tools at the time of planting are frequently used (Lowman 1986). Scalping or removing competing vegetation using hoes, shovels, hodads, or other hand-tools have been shown to be effective in grass communities. Scalps should be at least two feet in diameter and preferably larger (Miller 1986a). Compared to machinery, hand scalping offers more latitude for locating favorable planting sites. That is, locating sites with deep organic rich soil, away from aggressive competing vegetation, or behind logs that can provide shelter and protection. Site preparation (scalping) should be differentiated from clearing debris prior to opening a planting hole. Clearing is requisite to ensure that organic material (sticks, litter, etc) that may interfere with root to soil contact does not fall into the hole during planting. This can often be accomplished in situations in which soil is covered by litter, which can be cleared, exposing soil often covered with rich humus and fermentation layers. No matter which method of the site preparation used, it is critical that the soil is protected and maintained.

The use of machinery to prepare sites for regeneration is always a compromise between creating soil conditions for regeneration while maintaining and preserving soil productivity (fig. 12). The greatest limitations of mechanical site preparation are slope angle, soil compaction and displacement. As stated earlier, most early-seral species easily germinate and develop on the mineral soil that can readily be exposed by mechanical methods (Haig et al. 1941). A favored micro-site for natural regeneration or for artificial regeneration is one that prepares a weed-free planting/germination spot yet is in proximity to or conserves the nutrient- and water-holding surface organic layers (Graham et al. 1989, Graham et al. 1994a, Graham et al. 1995).

Fire

Fire can reduce fine fuels, prepare germination surfaces, reduce competing vegetation, preserve surface organic layers, and maintain appropriate amounts of coarse woody debris (fig. 11). However, unless fuel and weather conditions are appropriate, fire can create conditions adverse for regeneration and impair soil productivity (Debano 1991, Hungerford et al. 1991). The amount of forest floor consumed by a fire is dependent on its moisture content, particularly in the lower humus and fermentation layers. If the moisture content of these layers exceeds 100 percent when a fire occurs, the majority of litter and fine fuels (≤ 3 inches) do not burn and thus, are generally conserved (Ryan 1982). Under these moisture conditions, nutrients (such as P, N, K) can condense in the humus and fermentation layers and, therefore, are not lost from the site (Harvey et al. 1989). The temperatures at the mineral soil/organic layer interface usually do not exceed 300° C, the temperature at which N is volatilized (Hungerford et al. 1991). At this temperature, water-repellent layers are also less likely to

Figure 13—Shrubs can respond vigorously to prescribed fire.

occur even in coarse-textured soils. Burning when the lower humus layers are moist facilitates consumption of fine fuels, maintenance of CWD levels, and often results in exposure of micro-sites for planting and/or seed germination.

Some ground-level vegetation responds vigorously to heat such as *Ceanothus* spp. with its seed buried in the forest floor. Also, many ground-level species resprout aggressively in response to fire (fig. 13). Therefore, the amount, kind, and severity of fire used to prepare sites needs to be applied with an understanding of the expected response of competing vegetation for a given forest, PVT, and biophysical setting (Baumgartner et al. 1986, 1989).

Chemical Preparation

Chemicals are a very viable technique for site preparation. In particular, herbicides can target specific species or life forms and protect the surface soil layers that can be harmed by both mechanical and fire site preparation techniques. The latitude of site and weather conditions for applying herbicides may be less operationally restrictive than either fire or mechanical methods and, depending on the circumstance, the results may be more cost effective than using either of the other two methods (Baumgartner et al. 1986).

For the optimum growth of plantations, control of competing vegetation is essential. In the dry forests particularly (depending on the PVT), if ground-level vegetation is present before the regeneration harvest is applied, it will likely compete with future seedlings. Therefore, approximately two years prior to the harvest, an herbicide treatment an be applied to target the shrubby vegetation. Growing in the understory of a high forest canopy, shrubs tend to develop in sun-flecks, be single stemmed, spindly, and weak, thus making them highly susceptible to control by herbicide. When the regeneration harvest is applied, the ground-level vegetation will be absent providing ample planting sites. In contrast, if the chemical treatment is applied after the harvest treatment, ground-level vegetation will most likely be the risk of greater injury to the plantation, delaying the site preparation benefits.

Herbicides used for shrub control in forests include 2,4-D, glyphosate, imazapyr, picloram and triclopyr. To control grasses and forbs, atrizine, 2,4-D, sulfometuron, and hexazinone are suggested (Coop 2004). However, specific time of application and effectiveness of herbicide to affect targeted vegetation varies. Specific details on application and target species are available through the Pacific Northwest 2004 Weed Management Handbook (Coop 2004).

An area mechanically prepared or burned, may provide an ideal setting for the germination, establishment, and development of tree seedlings, but these same conditions are an ideal habitat for weeds (fig. 13). Weeds will quickly develop and compete with the planted seedlings for water, nutrients, occasionally light, and under some circumstances they may be allelopathic, which can further retard seedling development (Ferguson 1991). Pre-emergent herbicides can be applied to the surface of the planting spot such as hexazanone, sulfometuron, metsulfuron, and atrazine products to control competing vegetation as it develops. It is very important to use the right chemical and the right amount to insure only the weed species and not the planted seedlings are affected. For example, sulfometuron and atrazine are poor choices to use when planting ponderosa pine and western larch, respectively (see Baumgartner et al. 1986 and Coop 2004 for discussions on herbicides and their appropriate efficient, and effective use).

REGENERATION

A requirement for the successful application of a silvicultural system is the timeliness of regeneration, its amount and composition. Environments conducive to seedling establishment can be directly influenced by the amount and composition of over-story retained (seed tree, shelterwood selection) and the intensity and extent of site preparation (mechanical, fire, chemical).

Natural Regeneration

The early-seral and/or preferred species for production forestry, e.g., ponderosa pine, lodgepole pine, western larch, Douglas-fir, and western white pine, readily regenerate naturally (Haig et al. 1941, Pearson 1950). Depending on the forest type and the PVT, natural regeneration may be a viable alternative in many settings using a variety of silvicultural systems. However, less control of the timing, amount, density, and consistency of plantation establishment is possible with natural regeneration compared to artificial regeneration.

The cheapest and most site-adapted regeneration can be achieved through natural regeneration. On ponderosa pine and Douglas-fir PVTs, ponderosa pine and Douglas-fir can be naturally regenerated if appropriate site preparation is accomplished (Shearer and Schmidt 1991, Shepperd and Battaglia. 2002). However, many factors such as seed crop frequency and size, animal predation on the seed, weather damage to seed, and the timing and proper seedbed preparation can make the accomplishment of successful regeneration easier said than done (Haig et al. 1941, Pearson 1950). For example, if the site preparation is not well timed with the production of seed, adequate germination substrate and establishment sites may not be available when seed is produced by the desired species. Weather favoring the regeneration might not occur even if the site preparation and seed crops were well coordinated. Western larch is a case in point. A weather event such as a frost injuring flowers or unexpected cold weather hampering germination can spoil the best-laid plans (Graham et al. 1995a).

Species vary widely in seed production and dissemination (Haig et al. 1941). Western redcedar and western hemlock produce larger and more frequent seed crops than most of their associates. For example, the interval between good seed crops in western larch is highly variable and is often greater than 10 years. The other tree species usually produce good seed crops at less than 5 year intervals. For all tree species, wind plays a major role in seed dissemination. Only lodgepole pine exhibits cone serotiny and the degree of serotiny present is variable within the cold forests (Lotan 1973). Mineral soil and burned-over surfaces tend to supply good soil-to-seed contact, maintain moisture levels conducive to seed germination, plus supply water to the roots as they develop. In the Northern Rocky Mountains, temperature tends to be one of the most critical factors for germination. Minimum soil temperature of 51° F is needed and temperatures between 71° and 81° F are preferred (Haig et al. 1941). Organic seedbeds tend to lose soil moisture faster than roots can develop thereby restricting seedling establishment. Douglas-fir, ponderosa pine, western white pine, and lodgepole pine have intermediate germination rates while western larch and grand fir have low germination rates. In addition, western hemlock and western redcedar usually have high seed germination rates and occasionally reproduce by sprouting. Because these species regenerate easily, they can interfere with the regeneration and development of preferred early-seral species.

In moist forests, it is critical to understand the role blister rust plays in stand development especially when using natural regeneration. Shelterwoods can be used to naturally regenerate western white pine and a large proportion of these seedlings would be susceptible to blister rust (Graham et al.1994b). However, Hoff et al. (1976) reported that over 19 percent of natural regeneration in stands suffering high losses from blister rust could be resistant to the disease (figs. 3, 10). Therefore, when western white pine regeneration is abundant (thousands of trees per acre), a number of the seedlings is likely resistant to white pine blister rust. Nevertheless, distinguishing rust resistant from nonresistant seedlings becomes problematic when the stands are cleaned (precommercial thinning to alter species composition or improve stand condition). The resistance level will not approach that of trees produced in improvement programs but there is an excellent chance that some of these naturally regenerated trees will survive and grow well enough to produce commercial products and provide genetic diversity in western white pine (Graham et al. 1994b Fins et al. 2001) (See section on enhancing the survivability of white pine through pruning).

Table 1—The genetic differentiation among populations of tree species. Adaptation of species is based on the environmental interval by which populations must be separated before there is a reasonable assurance that the populations are genetically different (Rehfeldt 1994)

	Environmental Interval		
Species	Elevation Range (ft)	Frost Free Days	Adaptation
Douglas-fir	650	18	Specialist
Lodgepole pine	720	20	Specialist
Engelmann spruce	1215	33	Intermediate
Ponderosa pine	1380	38	Intermediate
Western larch	1480	40	Intermediate
Western redcedar	1970	54	Generalist
Western white pine	none	~90	Generalist

Artificial Regeneration

Because of the uncertainty of natural regeneration, artificial regeneration often provides more assurance and options for timely stand establishment and species composition, micro-site selection, tree density, and horizontal tree distribution. In addition, artificial regeneration offers opportunities to plant improved stock. Currently (2005), improved planting stock is available for western white pine, lodgepole pine, western larch, Douglas-fir, and ponderosa pine. The improvement developed in breeding programs includes improved tree growth, increased disease resistance, increased cold hardiness, and improved tree form compared to trees naturally regenerated.

However, care needs to be exercised to ensure that trees planted are ecologically adapted to the sites. For example, the environmental interval in elevation in which ponderosa pine populations show habitat specificity is approximately 1380 feet or 38 frost-free days (Table 1). In contrast, no habitat specificity in elevation has been found for western white pine and the habitat specificity interval in frost-free days is 90. The narrowest habitat specificity for any Rocky Mountain conifer occurs with Douglas-fir which has an environmental interval of 650 feet in elevation or 18 frost-free days (Table 1) (Rehfeldt 1994). Therefore, Douglas-fir is considered a specialist and western white pine a generalist in their species' adaptability to sites. Beginning in the early 1900s and in earnest during the 1930s during the Civilian Conservation Corp era, a major ecological mistake was planting off-site (seedlings not adapted to their environment) ponderosa pine seedlings throughout the West. Today, these off-site plantings are often dying from insects and disease and producing malformed trees. Unfortunately, a maladapted forest is being propagated, thus showing why it is critical that seedlings be ecologically matched to the site on which they are planted (Rehfeldt 1994).

Probably no other species is more suited to artificial regeneration than western white pine because of the good nursery and planting practices that have been developed over the last 100 years. With the introduction of blister rust from Europe in the early 1900s millions of white pine were killed. When all control efforts (e.g., killing the alternate host Ribes spp., fungicide application) failed, the future of western white pine management in the western United States appeared bleak (Ketcham et al. 1968). By 1950, the Office of Blister Rust Control, Northern Region of the USDA Forest Service, USDA Forest Service Northern Rocky Mountain Forest and Range Experiment Station, and the USDA Forest Service, Pacific Southwest Forest and Range Experiment Station began a program to develop rust-resistant western white pine. By 1985, seed orchards were producing a second-generation of western white pine that were 65+ percent resistant to the disease (a portion of the trees do get infected but survive) (Bingham 1983). The goal of the white pine tree improvement program was to increase its' resistance to blister rust and to accomplish this by using multiple genes, thus minimizing potential disease mutations (Fins et al. 2001). With this multi-gene approach the rust may infect and even kill some trees, but many trees, even if they become infected, continue to survive and grow to a saw timber rotation of 60 to 80 years (Graham et al. 1994b) (figs 2, 3, 9, 10).

In general, there are two types of seedlings that are planted, bare-root and container grown, and both have their place in production forestry. Bare-root seedlings are usually lifted from the nursery beds in the early spring for planting in the spring. Depending upon the silvicultural method and site preparation, a different size and age of seedlings can be specified. In addition, a key characteristic of a proper root-to-shoot ratio can be specified. Generally, seedlings less than three years old can readily be planted. Large-sized seedlings often offer a higher success of establishment compared to smaller seedlings because of their ability to rndure competing vegetation, damage from animals, or harshness of site. Seedlings with large diameters may be specified for areas prone to vegetation, woody debris or snow potentially pushing over small seed- lings (Schubert and Adams 1971, Baumgartner and Boyd 1976, Cleary et al. 1978).

Great strides have occurred in recent years in producing container-grown seedlings that meet a wide range of specifications. This can be accomplished by controlled growing conditions and by different sized and treated containers. In addition to a variety of seedling specifications, seedlings can be produced to plant during different planting cycles determined by the site and management objectives. As with most bare-root seedlings, container seedlings are most often planted in the spring but they can also be grown for planting in the fall (Landis et al. 1990, Landis et al. 1992).

Under special circumstances, seedlings can be planted in the summer if they are properly conditioned. Such situations exist when high elevation areas are not available to plant during the spring or fall because of snow. In the greenhouse, seedlings can be artificially moved through a growth cycle from bud burst through shoot elongation and bud set in a matter of weeks. By doing so, dormant seedlings can be planted during the summer (Landis et al. 1990, Landis et al. 1992).

Even though seedling production from seed collection through planting has been investigated and refined for 100 years, the successful completion of the entire regeneration process is often problematic. Seedlings well prepared in the nursery/greenhouse need to be handled with utmost care while in storage and on the planting site to ensure a dormant seedling is planted (Schubert and Adams 1971, Baumgartner and Boyd 1976, Cleary et al. 1978).

We suggest that choosing desirable micro-site positions that offer protection, have organic matter rich soil, and are free of competing vegetation is preferable to planting on a rigid grid. In most production operations and to minimize future tending operations, 200 to 250 trees per acre would suffice. A preferred micro-site for planting trees includes: places with adequate soil moisture, soil temperatures exceeding 40° F, uniform root-to-soil contact, and no soil impediments that would distort roots (e.g., produce J-rooted seedlings). In high organic soils, container-grown stock appears to do better than bare-root stock because root-to-soil contact can be more readily achieved (Schubert and Adams 1971, Baumgartner and Boyd 1976, Cleary et al. 1978).

Animal Damage

A variety of animals (insects, rodents, omnivores, ungulates, and livestock) may damage tree seedlings by eating, browsing, trampling, and breaking limbs. Animals including, but not limited to, porcupines (*Erethizon dorsatum*), pocket gophers (*Thomomys* spp.), cattle, sheep, hares (*Lepus* spp. and *Sylvilagus* spp.), black bear (*Ursus ameri-canus*), deer (*Odocoileus* spp.), and elk (*Cervus* spp.) can damage seedlings of most western tree species. The potential for damage should be thoroughly evaluated prior to implementing the silvicultural system (Kingery and Graham 1991, Knapp and Brodie 1992).

A variety of preventive and remedial techniques have been tested with mixed results. These have included providing an alternative food source or planting unpalatable tree species (Black and Lawrence 1992), modifying habitat to disfavor specific browsing animals, physically or chemically protecting tree seedlings, frightening browsers away, and trapping or killing browsing threats. Unfortunately, one method does not solve all browsing problems. Many recommend large planting stock because it typically is less vulnerable to animal damage (Loucks et al. 1990, Cafferata 1992, Graham et al. 1992, Marsh and Steele 1992). Nolte (2003a) suggested using a five-step process to reduce the effects of animal damage: 1) assess the severity and potential damage if no action is taken, 2) evaluate the feasibility of alleviating the problem, 3) develop a strategy prior to browse damage prevention measures, 4) implement a program, and 5) monitor the consequences. The preferred approach will depend on the results from site-specific monitoring and the most effective treatment may require integrating several methods within the silvicultural system.

Physical protection of seedlings with polypropylene mesh tubes is an option and appears to be successful in some cases (Black and Lawrence 1992). Fencing areas to keep livestock out can be effective, but expense limits its use (Nolte 2003b). Other forms of physical deterrents might be possible. Graham et al. (1992) noted that seedling damage from livestock fell below 10 percent when coarse woody debris (> 3.0 inches in diameter) was greater than 30 tons per acre. In some cases, minimizing disturbance avoids creating habitat that may increase pocket gopher populations (Marsh and Steele 1992). For example, the grasses that exist on a site can be killed using hexazanone (most commonly Velpar®), and this, in turn, will dissuade gopher use. Pocket gopher predation on planted seedlings is highest the first summer that the trees are planted and the first two winters (Ferguson 1999). Studies have shown that controlling pocket gopher populations with strychnine baiting poses relatively little risk to non-target species (Arjo

2003) but the effects of removal may be short-lived since replacement animals usually occupy the vacant habitat, thus necessitating the repeated application of treatments for maximum efficacy.

FOREST TENDING

The silvicultural system does not end with the regeneration treatment (i.e., clearcut, seed-tree, etc.). After a stand is regenerated or entered, stand tending is generally warranted to ensure the desired stand structures and compositions are developed and maintained (Fisher 1988). Tending activities (i.e., thinning, cleaning, weeding, liberation (overstory removal), sanitation, and fertilization) can occur at a variety of time intervals and intensities depending on forest type, PVT, species present, and past stand development. Release of species after periods of crowding or suppression is directly related to the length and vigor of the crown (McCaughey and Ferguson 1988, Ferguson 1994). Generally, shade intolerant species respond well to release after suppression and intolerant species respond poorly. Lodgepole pine, which often regenerates prolifically, is prone to stagnation early in its development, making later release cuttings less effective (Johnstone and Cole 1988). Therefore, stand tending is an integral part of both even-aged and uneven-aged silvicultural systems. Treatments can occur within all canopy levels and many intermediate treatments can produce forest products (Graham et al. 1999b).

In contrast to not acquiring enough regeneration, the issue in many forests is excessive regeneration that makes weeding and cleaning plantations (natural stands) essential for satisfactory development. For example, in the ponderosa pine forests of the Black Hills in South Dakota, ponderosa pine regeneration is often so prolific it creates a fire hazard and compromises future stand development options (Shepperd and Battaglia 2002). Similarly, in the cold forests, over-abundant lodgepole pine regeneration is often the norm, again making tending operations imperative if the stands are going to develop productively (Johnstone and Cole 1988) (fig. 4). Within the moist forests, natural regeneration is often plentiful making cleaning and weeding operations a necessity (Haig et al. 1941, Deitschman and Pfister 1973 Graham 1988) (fig. 9).

Weedings

Weedings occur during the sapling stage of stand development to remove competitive vegetation, such as specific trees or shrubs, and other vegetation that may compete with crop trees (Smith et al. 1997, Helms 1988). Weedings tend to be applied before or simultaneously with cleanings (treatments aimed at redistributing stand growth to selected stems). Most often weedings are essential in mixed-species stands and those prone to robust development of mid– and late–seral trees or when grass or shrub development interferes with stand development (Deitschman and Pfister 1973, Miller 1986b). In dry forests, this often occurs where grand fir and/or white fir, Douglas-fir, ninebark, or *Ceanothus* spp. tend to aggressively compete with ponderosa pine. Similarly, in the moist forests, grand fir, western hemlock, and alder are frequently removed to favor western white pine and western larch. Weedings can be accomplished most often mechanically or chemically and, in rare situations, fire can be used to weed a plantation of unwanted competing vegetation (Saveland and Neuenschwander 1988).

Chemical

Frequently, within a year or two after plantation establishment, even on settings where the competing vegetation was removed during site preparation, weeds tend to return and interfere with seedling development (Petersen 1986). Weeding young stands with herbicides is a viable alternative on many settings. However, specific time of application and effectiveness of the herbicide to affect targeted vegetation varies (specific details on application and target species are available through the Pacific Northwest 2004 Weed Management Handbook (Coop 2004). The actual timing of when weeds interfere with tree growth depends on forest type, PVT (weed species present and their ability to colonize or survive), type and success of the site preparation applied (Noste and Bushey 1987, Baumgartner et al. 1986). Herbicides that can be applied over the top of established seedlings and have been successful in controlling weeds include several hexazanone products (e.g., Velpar®, Pronone®). These herbicides are effective in removing weeds without damaging most conifers except western larch. Sulfometuron (Oust®) also removes weeds readily but is not preferred for use with ponderosa pine because of potential tree damage. Granular herbicides can be applied with a "weedometer" that distributes herbicides within a 3 to 5 foot radius of seedlings. Glyphosate (Roundup®, Accord®) can be directionally applied to weeds between trees and shields (e.g., PVC-plastic) can be used to apply herbicides within close proximity of seedlings.

Within 4 to 6 years on some PVTs, tall shrubs (e.g., maple, alder, willow) not controlled by a pre-harvest herbicide, readily sprout and often aggressively compete with planted trees (Lotan 1986). Imazapyr (a compound in Arsenal®, Chopper® and Onestep®) can be aerially (helicopter) or hand (backpack sprayer) applied to control this high shrub competition. Glyphosate, applied as a directed spray, can be used to control tall shrub competition as well as hexazanone, applied in the form of Pronone®. In northeastern Oregon, Oester et al. (1995), found that hexazanone, applied as a spot or broadcast spray, increased both survival and growth of planted ponderosa pine. It has been found to be more effective (more toxic) at controlling weeds when it is applied in conjunction with N fertilizers compared to applying the herbicide alone. When applied in this fashion, Pronone® has been found to be toxic to conifers even though the dose was believed to be safe. Presumably, the addition of N makes both the conifers and weeds grow later in the growing season thus making them both vulnerable to the herbicide. The most effective combination of N fertilizer and Pronone® will probably use smaller herbicide dosages, such as only ½ to ¾ of the amount that would be used when applied by itself. The combination of fertilization and weed control should enable stands to develop more quickily than would occur after the application of a single treatment.

Most conifers have a high tolerance for hexazanone and imazapyr, while most grasses and woody (dicot) species are very susceptible. Western larch, however, is very susceptible to damage from both of these herbicides. In most settings, a directed application of gyphosate using a backpack sprayer will control unwanted vegetation in western larch stands. The exact weeding approach and chemicals used will depend on the forest, PVT, biophysical setting, and nature of the competing vegetation (e.g., life form, species, size, distribution) (Coop 2004).

Precommercial Thinning (Cleaning)

Precommercial thinnings are applied during the sapling stage of stand development where specific trees are kept and others are removed so that growth of selected stems is favored (Smith et al. 1997).

In general, all of the early-seral species (ponderosa pine, lodgepole pine, western white pine western larch, and Douglas-fir) respond positively to precommercial thinning (Schmidt 1988). Of course, the magnitude of the response is predicated on the PVT and the biophysical setting. However, with judicial control of planting densities, the need for thinning to redistribute growth to selected trees should be minimized. In stands with prolific natural regeneration (such as may occur with western larch, western white pine, lodgepole pine, and on some sites, Douglas-fir and ponderosa pine), precommercial thinning is necessary to distribute the site's growth potential to a manageable number of trees that will result in future tree sizes consistent with predicted markets for wood products (Schmidt 1988).

Moist Forests

Within the moist forest, the most important period in the life of either a plantation or a natural stand is between 10 and 30 years. Prior to this time, stand densities have minimal impact on tree development. During this 10- to 30-year period, species composition and future stand dynamics are largely determined. Past this age, stand improvement can be accomplished only at high expense and at a heavy sacrifice to growing stock (Davis 1942). Western white pine over 30 years old will respond to release, but the required wide tree spacings will reduce stand yields (Deitschman 1966). Four hundred trees per acre at age 30 appear to be a good goal. These densities provide for good diameter growth, good volume production, and future thinning opportunities. The timing of cleaning a western white pine stand is a compromise impacted by waiting as long as possible to allow blister rust to be fully expressed, maintaining canopy closure to discourage *Ribes* spp. and competing conifer regeneration, and to treat stands early as possible so as to not create an unmanageable fire hazard (abundance of fine fuels) (Graham 1988).

Western larch also readily responds to precommercial thinnings at 10- to 15 –years of age (Schmidt and Seidel 1988). Though expensive, thinning of extremely dense stands, containing 1,000 to 25,000 stems per acre, will respond well to thinning. During these treatments. mistletoe can also be removed from the stand. Western larch benefits greatly from early thinning because it relieves overstocking and allows larch to capitalize on its rapid juvenile growth. Schmidt and Seidel (1988) suggest that stocking levels for western larch range between 45 and 75 percent of normal stocking or in the range of 400 trees per acre or less. Thinning dense stands transfers growth to fewer numbers of rapidly growing trees, thus maintaining good vigor and crown development, increasing resistance to wind, snow, and insects, and permitting more uniform diameter growth. Judicious thinning regimes can result in shorter rotations and increased merchantable yields. Target Douglas-fir densities also fall in the range of 400 trees per acre in precommercial thinnings in the moist forests (Lotan et al. 1988). It appears that the greatest benefit from thinning in mixed stands of western white pine and associates is to improve stand and tree quality. Cleanings do not increase overall volume production, but do increase future value of stands by concentrating growth on fewer, selected better quality trees.

Western White Pine Pruning—Most lethal blister rust infections occur in the lower crown when trees are quite young (≈15 years). Pruning the lower branches of white

Figure 14—A precommercial thinning (cleaning) in a sapling-sized ponderosa pine stand. Note the large amounts of fuel produced, which is a common occurrence, and needs to be decreased to protect the stand from severe wildfire.

pines to a height of 8 to 10 feet, but not reducing the live-crown ratio to less than 50 percent, appears to offer the tree some protection from blister rust infection while not substantially reducing tree growth rates. In addition, removal of any branches with cankers greater than 6 inches from the bole greatly increases the chances of the tree surviving to produce a commercial product. Schwandt et al. (1994) showed that by cleaning western white pine stands (10 to 18 years old) to a spacing of approximately 10 feet by 10 feet and pruning the lower branches, the value (1992 prices) per acre (22 years later) of the white pine doubled in the treated stands ($2000 per acre) compared to that of untreated stands ($1000 per acre).

Cold Forests

Natural stands of lodgepole pine, which commonly regenerate following wildfire, are frequently dense (Johnstone 1985, Johnstone and Cole 1988). Likewise, stands that regenerate following harvest and site preparation (scarification and/or prescribed fire) often establish in dense clumps. Even when lodgepole pine is planted or cleaned at an early age, ingress of seedlings may result in denser stand conditions than desired. Lodgepole pine does not self-thin well on any PVT; thus without treatment dense stands tend to remain dense. In these situations, tree growth is suppressed and stands are subject to heavy mortality from snow and wind. Consequently, stand yields will be well below the capacity of the site.

Determining thinning densities for all species and, in particular lodgepole pine, the optimum management density is a tradeoff between tree size and stand volume objectives. Young lodgepole pine responds more readily to density reductions compared to old trees (Murphy et al. 1999). Merchantable cubic volume production per unit area is maximized at relatively high (≈1000 trees per acre) initial stand densities. A single precommercial thin (≈400 trees per acre) at age 20 on many sites would produce commercial yields by age 40 compared to never producing a commercial product by age 120 years without the treatment (Cole and Edminster 1985). However, for most management considerations, cutting cycles of 30 years seem feasible and offer commercial yields at several points during the rotation (≈ 120 years).

Dry Forests

Within the dry forests, the upper level management zone for Douglas-fir approaches ≈2000 trees per acre of 3 inch diameter trees. However, a more realistic precommercial thinning density would approximate 450 trees per acre and, of course, these estimates would be predicated on the future management options and product needs. A target of 140 to 220 ft^2 of basal area and 60 to 100 trees per acre would be the range of tree densities that would be preferred for most Douglas-fir settings (Lotan et al. 1988).

The upper management zone (tree density) for ponderosa pine is, for the most part, roughly based on threshold levels of risk for bark beetle attacks. The lower level of stocking for ponderosa pine is largely determined on the stand density in which regeneration is likely to occur (fig. 14). The highest stand densities for precommercial thinning would be in the range of 700 trees per acre and the minimum values would be in the range of 200 trees per acre. Target stand densities should not exceed 150 ft^2 of basal area and minimums in the range of 50 ft^2 would suffice in most situations (Edminster 1988). As with other species, these values would be based on the PVT, biophysical setting, management objectives, and the markets available for products. Significant declines in volume production will be realized with low residual stand densities. If rapid development of merchantable–sized material is a goal, than the lower residual stand densities are desirable. On lower productivity sites, more than one precommercial thinning may be required to maintain the desired stand structures. Low initial stand densities, either through planting or cleaning, may greatly influence thinning opportunities.

Thinnings

Beyond the sapling stage, thinnings redistribute growth potential to fewer trees leaving stands with the desired structure and composition. Even though thinning from below is the most common method, there are other methods that have applicability depending on the forest, PVT, and management objectives and desires of the landowner. Low (thinning from below), crown (thinning from above), selection (diameter-limit thinning), free thinning, and mechanical thinning all have application in the moist, cold, and dry forests of the Inland Northwest (Nyland 2002, Smith et al. 1997).

Low thinning is when trees are removed from the lower canopy, leaving large trees to occupy the site. This method mimics mortality caused by inter-tree competition or surface fires and concentrates site growth potential on dominant trees. Low thinnings primarily remove intermediate and suppressed trees, but heavy thinnings can also remove many in the codominant crown class. Low thinnings not only remove understory canopies but can also alter species compositions. Usually, different tree species have characteristic development rates that result in individual species dominating specific canopy layers. For example, in dry forests, ponderosa pine primarily occupies the dominant canopy layers, whereas shade-tolerant grand fir, white fir, or Douglas-fir occupy the intermediate and suppressed layers. A low thinning in these stands therefore favors the development of the dominant and codominant ponderosa pine. Depending on the desired stand structure, low thinnings can remove few to many trees. Also, thinnings need not create regular spacings but rather can vary both the number and degree of clumping of residual trees.

Crown thinning, or thinning from above, reduces crowding within the main canopy. Dominant and codominant trees are removed to favor residual trees in these same classes. This method is used to remove selected trees in the dominant and codominant crown classes that are competing with more desirable trees (Nyland 2002). Selection thinning removes dominant trees to favor smaller trees. This method is often applied by removing trees greater than a certain diameter. Diameter-limit cuts that continually remove the largest trees may well be dysgenetic and can be a disguise for high grading (removing trees of high economic value without concern for future stand development). By maximizing removal of the current value from a stand, future options may be limited and the only recourse for the future may be to regenerate. Stand structures and species compositions created by using selection thinning are limited and, in general, favor shade-tolerant species or trees occupying the intermediate and suppressed crown classes. Often the stands created by selection thinnings are prone to epidemics of insects and diseases. Compared to the other thinning methods, selection thinning is less useful in these forests because of the limited stand structures and compositions it creates.

Free thinning, sometimes called crop-tree thinning, primarily releases selected trees. This method favors specific trees, whereas the remainder of the stand goes untreated. Depending on what is presented in various portions of a stand (tree spacing, species, vertical structure, etc.), the thinning criteria can be highly flexible and produces stands with large amounts of diversity. It can be used in any of the crown classes for releasing specific trees. This method has the most flexibility for creating various stand structures and compositions.

Mechanical thinning removes trees based on specified spatial arrangements (Nyland 2002). This method is often applied in plantations where every other row or every other tree in a row is removed. Such a rigid thinning prescription

Figure 15—Helicopters can be used to apply nitrogen fertilizer (urea pellets).

is easy to apply, but the stands created often lack diversity in either structure or composition. This method also resembles strip thinning, where a strip of trees is removed. Mechanical thinning may be well suited for timber production on uniform sites but has limited value for producing conditions that meet other resource values.

Use of herbicides following any form of thinning has rarely, if ever, occurred in an Inland Northwest forest. Nevertheless, there are some situations where past heavy thinning and/or patchy stocking have created stands with substantial biomass in competing vegetation. In these situations some form of herbicide application might be appropriate to maintain the desired forest structure. The repertoire of herbicides that might be considered at this point would be very similar to those applicable for use in stand weeding.

Fertilization

As stated earlier, nitrogen (N) is the most limiting nutrient in the Inland Northwest and the greatest growth response comes from the addition of N (fig. 15). The combination of stand density control, along with the application of N, appears to be the best approach for managing young stands and accelerating their growth and crown development (Graham and Tonn 1979, Weetman et al. 1985, Moore 1988, Moore et al. 1991)

Within the dry forests, ponderosa pine shows a strong linear response up to approximately 400 pounds of N per acre. Plantations with weed control can show twice the fertilization response as unweeded plantations (Powers et al. 1988). Powers (1988) found that volume growth was nearly four times greater with weeding than no treatment but the combination of fertilization and weeding produced volume growth nine times greater than untreated stands. Similarly, Douglas-fir can be rather responsive to fertilization and response varies by stand density, soil parent material and pre treatment N. Two-hundred pounds per acre appears to be a good treatment and the response appears to last about 6 years but most likely depends on stand density (Moore 1988).

Within the cold forests, lodgepole pine grows on some rather infertile sites making it respond dramatically to improved nutrition, especially following precommercial thinning (Weetman 1988). Some evidence suggests that thinning, along with fertilization, increases lodgepole pine's resistance to attack by mountain pine beetle. Also fertilizing in the spring prior to bud burst seems to provide the best response. Hamilton and Christie (1971) showed that mean annual increments of 172 to 214 ft^3 per acre were achievable by fertilizing prior to crown closure.

There is a shift of nutrients from soil to tree, once the canopy is closed. As the tree's demands on soil rapidly decline following canopy closure, the nutrient cycles within the tree and through the tree-litter system are then fully charged (Weetman 1988). The cycle within the tree is based on the recovery and reuse of nutrients prior to the death of old tissues, including those of the leaf before abscission, and can be up to 85 percent efficient. However, the slow release of N from litter can lead to late-rotation (≈ 60-80 years) N deficiency. In Oregon, fertilization of a 40-year-old closed-canopy lodgepole stand with 600 pounds of N per acre produced an 8-year volume response of 79 percent over a control stand and 370 pounds of N per acre produced a 3-year volume response of 87 percent over a control (Cochran 1979).

Within the moist forests, grand fir is very responsive to fertilization. The other species appear to be well adapted to the nutrition regime of the moist forests. This lack of fertilization response could possibly be related to the prevalence of the nutrient-rich volcanic soils. It also appears that western white pine has wide amplitude of N demand (Graham and Tonn 1979).

Most conifers favorably respond to the application of N at the time of planting, especially in concert with competitive vegetation control and proper site preparation. One option is to apply nutrients in the nursery which will provide robust root growth and enhance establishment when the seedlings are planted. Another opportune time to apply fertilizer is when a planting is about 5 years of age. Both of these fertilizer applications tend to further plantation establishment and increase juvenile tree growth.

STAND MANAGEMENT PLANNING

In the Inland Northwest, stand density studies, in particular thinning and precommercial thinning (cleaning and weeding), have been conducted for nearly 100 years. The concept of yield tables and normal stocking was produced from this research (Haig 1932). In some settings, the information in these yield tables are as valid today as the day they were produced (1930s). The concept of site index and the site index curves produced during that time are also still very applicable (in 2005).

However, today there are more precise and robust tools available for stand management planning. In particular, the Forest Vegetation Simulator (FVS), with variants available for areas across the United States, can be calibrated to a given site and species mix (Dixon 2002). FVS contains three major components: regeneration establishment, small tree development, and large tree development (Wykoff et al. 1982, Ferguson et al. 1986). These components can be related to the physical setting based on location, slope, aspect, elevation, PVT (e.g., habitat type, plant association), site index, and stand density index. The small-tree component can be calibrated to a specific site by inputting the periodic height increment of seedlings and saplings and the large-tree component can be calibrated by inputting the periodic diameter increment of large trees (Dixon 2002).

All three components work in concert to project stands into the future by incorporating various management activities including harvesting, site preparation, planting, thinning, pruning, and fertilization to name a few. The influence these and other stand treatments have on stand development can be projected into the future and displayed using a variety of stand metrics. Some of these include: stand diameter, height and species distributions, total and merchantable volume distributions by species and diameter, volume accretion and mortality by diameter and species, total and merchantable removals by diameter and species, amount and characteristics of regeneration by species and individual tree characteristics. Several extensions are available to display attributes such as those related to wildfire and fuel treatments, root diseases, blister rust, bark beetles (e.g., Douglas-fir beetle (*Dendroctonus pseudotsugae*), mountain pine beetle (*Dendroctonus ponderosae*)), and defoliators such as the spruce budworm (*Choristoneura occidentalis*) and tussock moth (*Orgyia pseudotsugata*). The FVS output can be customized for desired time intervals, readily linked to economic analysis, and pictorially displayed using the Stand Visualization System. And, most importantly, FVS can be linked to geographic information systems making the management tool both spatially explicit and providing information at resolutions customized for each owner and application (Dixon 2002).

SUMMARY

Silvicultural systems describe the planned treatments through the life of a stand and are documented in a silvicultural prescription (Smith et al. 1997, Nyland 2002). By doing so, all of the treatments and their expected outcomes from stand establishment through tending activities are integrated and designed specifically for the biophysical environment presented and designed to meet the management objectives for that stand fulfilling the goals of the land-owner. Developing silvicultural systems for specific sites enables silviculturists to recognize the different vegetation complexes and successional pathways inherent to the moist, cold, and dry forests. In other words, one prescription does not fit all stands, especially for the different forests and environments intrinsic to the Inland Northwest.

In general, the early-seral species western white pine, western larch, ponderosa pine, Douglas-fir, and lodgepole pine, are the most resistant to native insects and diseases, the fastest growing, and the most aggressive establishers on the given potential vegetation type (PVT) on which they occur. For production forestry, the most appropriate regeneration method to apply in the cold forests is a properly applied clearcut. Likewise, within the moist forests, clearcutting provides good results but seed-tree and shelterwood regeneration methods are also applicable depending on the desired species mix and the biophysical setting (potential vegetation type, slope, aspect, current vegetation). Within the dry forests and especially on the grand fir and/or white fir potential vegetation types, clearcutting and seed-tree regeneration methods are very appropriate for the production of ponderosa pine and Douglas-fir. However, on the drier PVTs (e.g., dry Douglas-fir and ponderosa pine), a shelterwood system offers protection for the seedlings during the establishment period and may provide better results than the total or majority canopy removal of clearcutting and seed-tree methods. Two-stage shelterwoods (preparatory cut followed by a seed-cut) are suitable on ponderosa pine PVTs. Also, under most circumstances, selection systems are most appropriate for use on ponderosa pine PVTs for the production of wood crops.

The foundation of all forestry is the soil resource. The soil and its management in all phases of the silvicultural system need to be recognized. In many portions of the Inland Northwest, the residual soils are covered with volcanic ash and/or loess deposits enriching them and, more often than not, contain the majority of the site's productive potential. Frequently the biological and nutrient capital of a forest soil tends is near the surface of the mineral soil or integrated into surface organic layers. The humus, fermentation, and buried rotten wood layers in forest soils especially need to be recognized for their contribution to the nutrition of a site. In some settings, a major contributor to the organic matter on a site is coarse woody debris and it should be recognized and managed appropriately.

Because of the importance of soil and especially the nutrient rich (e.g., N) surface layers, we hope that the role these layers play in maintaining forest productivity will be more widely appreciated and suggest that these soil layers should only be scarified and/or scalped for a purpose. The contributions of ground-level vegetation to maintaining forest productivity in many settings should also be recognized. In particular, many shrubs and forbs fix N and ground-level vegetation can conserve both nutrients and soil in the face of catastrophic disturbances such as wildfire. Prescribed fire is an excellent tool for preparing sites for both natural and artificial regeneration, managing competing vegetation, and reducing the wildfire hazard. However, prescribed fire needs to be integrated into the silvicultural system and used judicially to produce desired conditions.

Each conifer species is ecologically adapted to a site and it is paramount that seedlings be adapted to the site on which they are planted. The ramifications of planting maladapted seedlings may not become apparent until the stand is developing disease and/or insect epidemics or the trees are malformed. Because the forest sites are so variable on a fine scale, all planting and tending activities should take advantage of the small differences inherent to a site and multi-species, multi-spacing plantings, cleanings, weedings, and thinnings should be considered and used where appropriate.

The benefits of using appropriate herbicides are often substantial when managing forests in the Inland Northwest. However, herbicides can be costly and environmentally difficult to use. Research continues on herbicide alternatives. For example, some research addresses herbicides that have not yet been tried in the Inland Northwest, some focuses on herbicide doses, some on formulation, and some on fertilizer-herbicide combinations. No doubt, herbicide use will continue to be a viable alternative for managing many Inland Northwest forests for wood production.

To facilitate stand and forest management planning, a calibrated, spatially explicit version of the Forest Vegetation Simulator (FVS) is an effective tool. FVS can be created and adapted to particular settings and provide realistic views of stand and forest management alternatives and their impacts on forest development over time. Various extensions of FVS are available for evaluating and displayi n g insect, disease, and wildfire impacts to a stand. Most importantly, FVS is a very appropriate way of integrating all aspects of stand establishment and tending into a silvicultural system and its use fosters documentation of silvicultural prescriptions.

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